# The Radio and Electronic Engineer

## Ionospheric Radio Wave Propagation




Vol. 45, No. 1/2
JANUARY/FEBRUARY 1975


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Volume 45 No. 1/2 January/February 1975

# The Radio and Electronic Engineer

## The Journal of the Institution of Electronic and Radio Engineers





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*Subscription Rates for 1975:*

| 1 year | 2 years | 3 years | Single copies |
|---|---|---|---|
| £14.00 | £25.00 | £35.00 | £1.25 |
| *USA and Canada* | | | |
| $38.00 | $68.00 | $96.00 | $3.50 |

ABC Member of the Audit Bureau of Circulations

Average monthly circulation for January-December 1973, 15,341

Member of the Association of Learned and Professional Society Publishers

Papers published in *The Radio and Electronic Engineer* are listed or abstracted as follows:

*Title listings:* 'British Technology Index'; 'Current Papers'; 'Topics'; 'Current Contents'; 'Science Citation Index'; ASCA.

*Abstracted fully:* 'Science Abstracts'; 'Referativni Zhurnal'.

*Abstracted selectively:* 'Chemical Abstracts'; 'Computing Reviews'; 'Acoustic Abstracts'; 'Solid State Abstracts Journal'; 'Nuclear Science Abstracts'.



UK ISSN 0033–7722

*Published monthly by the Institution at*

8-9 BEDFORD SQUARE, LONDON WC1B 3RG

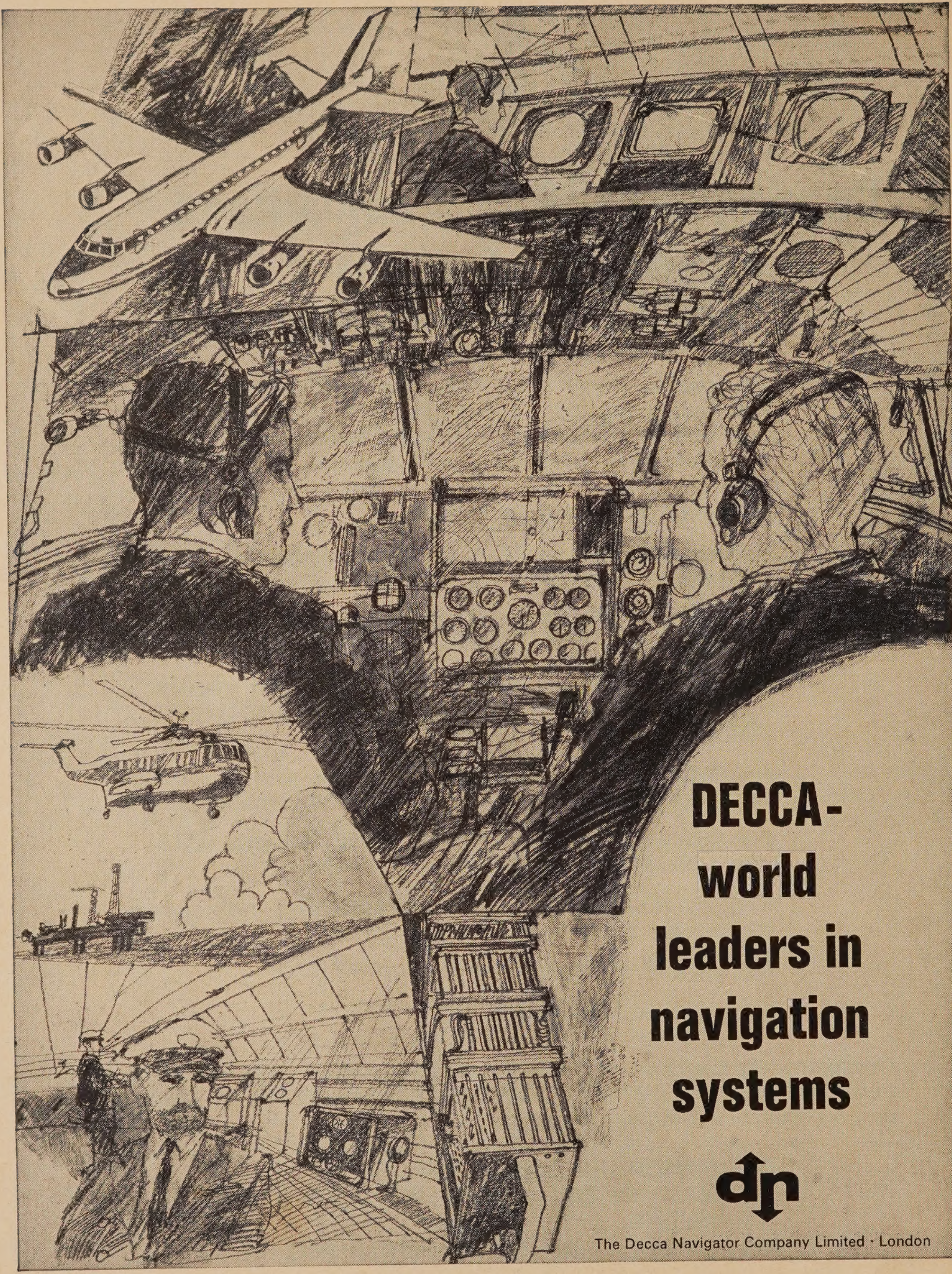
*Telephone:* 01-637 2771 (10 lines)

*Telegrams:* INSTRAD LONDON WC1

*Advertisement Department:*
Hill Center, 3 Chalk Hill,
Oxhey, Watford, Herts.
Telephone: Watford 21284



*Cover picture shows the Culgoora radioheliograph used in ionospheric research for observing radiation from solar flares. CSIRO Division of Radio-physics photograph.*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Incorporated by Royal Charter 1961

*To promote the advancement of radio, electronics and kindred subjects by the exchange of information in these branches of engineering*

Volume 45 No. 1/2 January/February 1975

# The Radio and Electronic Engineer

**The Journal of the Institution of Electronic and Radio Engineers**

## The Past and the Future

BORN in the aftermath of the first world war and, by incorporation, made legally respectable during a time of industrial depression, the Institution enters its second half-century ensconced in a Royal Charter and the shield of a Council of Engineering Institutions which it helped to create.

It would be idle to pretend that such achievements were easily gained. Public opinion, as formulated by successive governments, and private enterprise, was not easily convinced of the potential future of wireless—subsequently called radio and electronics—in defence, as a means of communication, or for public information and entertainment. Prejudice was overcome by the freedom given to the founders of the Institution to prove the need for such a society of engineers and to enlist the support of a free press—national and technical. In the press and elsewhere founders of the Institution argued the case for encouraging universities and other teaching establishments to provide training and laboratory facilities for students wishing to create for themselves careers in radio and electronics.

This freedom to express opinion which enabled the IERE to prosper must not be denied in turn to those who now wish to deny the worth of separate Institutions and who argue, no doubt sincerely, that the present and future development of technology would be better served by one amorphous, all-embracing body of engineers. As in 1925 and again in 1932, the present world economic state provides a fertile ground for arguing cut-backs in costs, savings for the individual and other seemingly attractive formulae. But how much of the arguments is based on prejudice and inability to plan a future society able to meet human needs?

Prejudice must be fought; whether it be engendered by an element of failure to secure personal aggrandisement or a corporate desire to belong to 'the biggest' it is necessary to face the truth on the true functions of a professional body.

Without doubt there are some members of all fifteen chartered engineering Institutions whose decision to seek membership was based wholly on the personal rights and benefits expected from 'belonging' to a particular Institution. Equally without doubt there is a very strong argument in favour of securing for chartered engineers the same public esteem given to such as the medical, legal and accountancy professions. It is therefore right and proper for professional engineering bodies to promote this public recognition of the qualifications of its members.

All this does not, however, gainsay that an equally important function of each professional body is to encourage development of the art it represents and the training of future entrants to its own branch of the engineering profession. Without that foresight the profession as a whole must decline in importance.

In our materialistic world it may seem trite to suggest that an individual member has a moral obligation to contribute to the profession from which a living has been derived. What other purpose however could have motivated the founders of our own Institution, lacking as they did the status this Institution now enjoys?

The spirit of its founders continues to permeate throughout the IERE. For that reason, as well as its previous experience of surmounting economic difficulties, the Institution may well look forward with confidence to celebrating its Golden Jubilee as a stepping stone to its Centenary.

G.D.C.

*Guest Editorial*

# Ionospheric Radio Communication

TO the engineer the ionosphere offers a comparatively cheap and easy method of communicating well beyond the horizon. The l.f. and v.l.f. bands have been in use since the beginning of the century, while the h.f. band with its much greater spectral width, and which also allowed communication to great distances with low power, was discovered in the early 1920s. The engineer soon found, however, that the propagation characteristics were extremely variable in both time and space. Largely because of this variability, and because of the signal dispersion, h.f. ionospheric communication has a reputation for poor reliability—a reputation which is self-perpetuating since it is all too easy to attribute any communication difficulty to propagation conditions.

The scientist, on the other hand, observes the ionosphere as a part of the Earth's atmosphere. He may use radio methods in his observations—and for many years ground-based radio soundings were the only means of observation—or he may be concerned with the problem of radio wave propagation in the ionospheric plasma under the influence of the Earth's magnetic field; but his interest is likely to be in the formation, structure and behaviour of the ionosphere itself, rather than in the application to the engineer's communication problems.

The ionospheric papers in this issue show how far our understanding of the ionosphere and of the interaction between the Sun and the Earth now extends. One milestone in studies of the ionosphere was the great co-operative observing programme undertaken during the International Geophysical Year, 1957–8. Studies made then, and in other subsequent co-operative ventures, together with *in-situ* measurements made by rockets and satellites and with the international organization for the exchange and storage of data, have dramatically increased our appreciation of ionospheric morphology and development. H.f. prediction techniques can now include detailed models of the electron density distribution and of absorption, although the complexity of the process is such that the prediction of the strength and polarization of each of several potential signal modes requires computer facilities. The day-to-day changes in the ionosphere which can be included statistically in long-term planning predictions arise largely from changes in solar radiation. Short-term forecasting up to, say, one day ahead depends upon an extensive network of real-time observations but, primarily, it requires an understanding of solar-terrestrial relationships and of the effects of individual solar disturbances. Two papers, one on l.f. and v.l.f. propagation and the other on h.f. tilts and travelling disturbances, also show how ionospheric phenomena can affect the design and performance of systems. In all such ionospheric work the scientist and the engineer work in close co-operation, indeed the radio wave propagation engineer finds himself very close to the border between the two professions, and this co-operation is highlighted in the paper which describes the work of the International Radio Consultative Committee.

Radio systems have developed with ionospheric knowledge. Frequency agility is required to follow ionospheric variations—and consequently prediction and forecasting methods are also required as is a sufficiently high level of operator training and experience. Real-time ionospheric sounding and channel measurement systems may reduce the demands on the operator in the future and fully automatic systems seem possible. The crowded spectrum, even now when satellite and cable systems take much of the trunk-route traffic, demands high frequency stabilities, narrow antenna polar diagrams and greater control and flexibility of transmitter power levels. Modulation systems are being developed which exploit to the full the capabilities of the medium so that data rates can be increased. Modern systems designed for specific h.f. requirements and operated with skill can now give a performance which is similar to that of other communication modes. The unreliability of systems where the demands of the propagation medium were not understood is now unnecessary.

This issue has set the ionospheric scene. Such a long established means of communication will often be overshadowed by the spectacular modern technology of satellite and cable systems. Nevertheless the demand for communication bandwidth, together with the unique advantages of the ionosphere, particularly when low-cost broadcast or mobile systems are involved, will ensure that the older systems will be brought up to date so as to fully exploit the resources of the radio spectrum.

L. W. BARCLAY

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# Developments in ionospheric physics since 1957

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and

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SUMMARY

The year 1957 marked the beginning of the International Geophysical Year and the satellite era, and this review describes the most important developments in ionospheric science since then. The discoveries made by different techniques concerning the nature and formation of the D, E and F layers and their various anomalies are considered and the relationship between the ionosphere and the region above it, the magnetosphere is briefly discussed.

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## Glossary

*Region* (*of ionosphere*). A part of the ionosphere, conventionally defined in terms of height: the D region lies below 90 km, the E region between 90 and 150 km, and the F region above 150 km.

*Layer* (*of ionosphere*). Refers to ionization formed within a given region and labelled accordingly; e.g. the E layer within the E region, F1 and F2 layers within the F region.

*Ionospheric Sounding.* In its simplest form, pulses of radio waves of about 150 μs duration are radiated upwards from a transmitter on the ground and are received near the same point after reflexion by the ionosphere. The time delay $\tau$ is measured and recorded as virtual height $h'$, where $h' = c\tau/2$ and $c$ is the velocity of light. Different heights are probed by sweeping the radio frequency, typically from 1 to 20 MHz in about 3 minutes.

*Ionosonde.* An instrument for carrying out ionospheric sounding.

*Ionogram.* The record produced by an ionosonde, showing virtual height as a function of frequency.

*Critical Frequency.* The highest frequency of radio wave which can be reflected from a particular ionospheric layer at vertical incidence. See caption to Fig. 1 for its relation to electron density.

*Chapman Layer.*[28] The simplest theoretical shape for an ionospheric layer formed by solar radiation.

*Nm*F2. The electron density at the peak of the F2 layer (similarly for other layers).

*hm*F2. The height of the peak of the F2 layer (similarly for other layers).

## 1 Introduction

An enormous amount of ionospheric research has been carried out since 1957, and we have had to be rather selective as to the topics that we shall consider. As readers of this journal are likely to be interested primarily in the part played by the ionosphere in radio wave propagation, we will pay most attention to the distribution of electrons therein, but will not ignore the fascinating discoveries of less direct practical importance which have been made. Much of our knowledge of the behaviour of the ionosphere, and particularly of its numerous anomalies, has resulted from the co-ordinated programme of observations begun during the International Geophysical Year (IGY, 1957-58) and continued during its successors, the International Geophysical Co-operation (IGC, 1959) and the International Quiet Sun Year (IQSY, 1964-65).

In the years under review there have been striking improvements in experimental technique; indeed completely novel methods have been introduced for certain measurements. The techniques will not be described here in detail, but some account will now be given of the most notable.

Among ground-based methods of investigation, the most important development has been the 'incoherent scatter' radar technique proposed by Gordon[1] in 1958. In this technique, high-powered signals are transmitted

upwards on a frequency high enough for most of the power to penetrate the ionosphere: in practice, frequencies as low as 40 MHz and as high as 1300 MHz have been used. A very small fraction of the power (typically 1 part in $10^{11}$) is scattered by the electrons in the ionosphere and can be detected on the ground with sensitive receiving equipment. The scattered power is directly related to the electron density, so the electron density distribution as a function of height can be obtained by using pulsed transmissions and measuring the received power as a function of delay time. This, however, by no means exhausts the capability of this technique, for by measuring the spectrum of the received signal much information can be deduced about the composition, temperature, and drift velocity of the ions and electrons in the ionosphere.[2]

Most of the other important developments in techniques make use of space vehicles. In the case of rockets, observations had started well before 1957 but it was not until after that year that significant numbers of reliable results became available. In one method a radio wave is transmitted from the ground and received in a rocket with measurement of the Faraday rotation of the plane of polarization; this has proved particularly useful in finding electron density in the D region, where conventional ionospheric sounding is of little help. At greater heights measurements with satellites are more effective; these utilize either probes measuring local ionospheric parameters or radio transmissions to or from the satellite which can give information on conditions at more distant points. Especially notable have been the topside sounding satellites, the first of which, *Alouette 1*, was built in Canada and launched by the USA in 1962. Each carries an ionospheric sounder and orbits well above the level of peak electron density; it makes use of the techniques employed with ground ionosondes, and can also observe certain plasma phenomena that depend on the fact that the transmitter is actually within the ionosphere. The great mobility of satellite-borne experiments has enabled us to learn many new facts about how the ionosphere varies from place to place, day to day and even hour to hour. Several important features not easily discerned from the ground have thereby come to light.

Much progress has also been made in the measurement of those incoming radiations which give rise to to ionization in the upper atmosphere. Here the advances are almost entirely due to the use of space vehicles, which carry measuring instruments to levels where the radiation is unaffected by the atmosphere. It is convenient to summarize the results obtained in this way by Fig. 1, which shows $N(h)$ profiles of electron density versus height in mid-latitudes and the principal ionizing radiations in each height range. All these radiations except the cosmic rays originate in the Sun. Most of them ionize commonly occurring atoms or molecules such as O or $N_2$, but an interesting exception is found in the D region, where the photons in the Lyman-alpha line at 121·6 nm are energetic enough to ionize only nitric oxide and not the major constituents. However, it turns out that there is quite sufficient nitric oxide present in this region to permit the observed electron density to be produced.

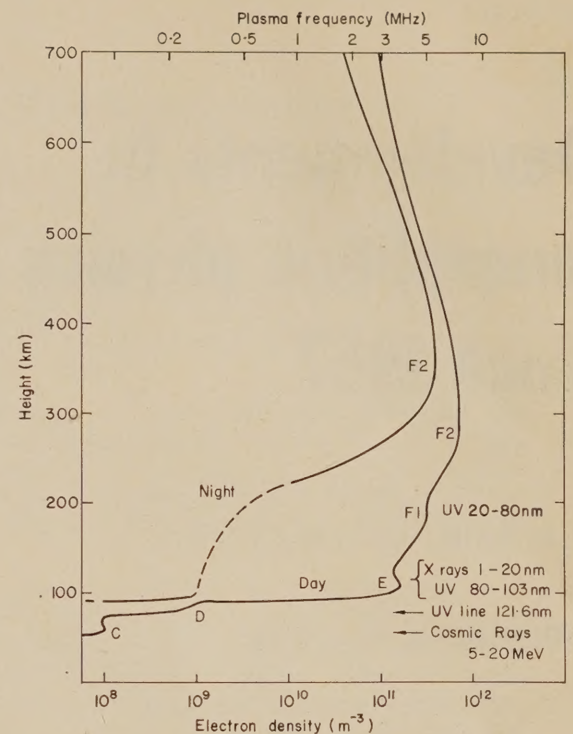


**Fig. 1.** Typical electron density distributions for summer noon and midnight conditions at mid-latitudes, and the principal ionizing radiations at each level. Plasma frequency $f_N$ (Hz) is related to electron density ($m^{-3}$) by $f_N = 9\sqrt{N}$; the plasma frequency at the peak of a layer is called the critical frequency ($f_0$).

## 2 The Lower Ionosphere: C and D layers

Before 1957 measurements of electron density below 90 km were very few indeed and not of great accuracy. However the position in 1957 represented a considerable improvement on the state of affairs in 1950, when nothing at all was known. In the period 1950-57 two important techniques were developed for studying the lower ionosphere, where the electron density is too small for conventional ionospheric sounding to be of value. These are partial reflexions (Gardner and Pawsey[3]) and wave interaction (Fejer[4]): however, substantial numbers of results only came from these methods after 1957.[5,6] Further results in this period also came from the rocket techniques mentioned in Section 1.

Figure 2 shows some examples of the electron density distributions in summer noon conditions at mid-latitudes.[6,7,8] The rocket distribution (a) and the other distributions (b) and (c) do not differ greatly above 68 km but there is a considerable separation between the curves at lower heights. However, if curve (a) is used to calculate the characteristics of v.l.f. and l.f. propagation, the results are consistent with observational data. A still better fit is obtained from curve (d), which was produced by Bain and Harrison[9] by modifying slightly a rocket distribution[10] and adding a C layer below 64 km. Note the close resemblance between curves (a) and (d) above 66 km. Electron density distributions have also been produced purely from v.l.f. and l.f. propagation results by Krashnushkin[11], Deeks[12] and Shellman.[13]

These propagation calculations would have been impossible without the development of 'full-wave' methods which utilize Maxwell's equations to calculate propagation characteristics, as is necessary at v.l.f. and l.f. since the properties of the ionosphere vary substantially within one wavelength so that the simple 'ray-tracing' techniques become invalid. Work on the calculation of ionospheric reflexion coefficients by 'full-wave' methods culminated in the period under review with Pitteway's paper[14] describing a very satisfactory computer treatment of the problem.

Virtually all of the calculations of D-layer electron density require a knowledge of the electron collision frequency, a parameter of importance in its own right through its close association with radio wave absorption at frequencies up to h.f. and indeed v.h.f. Since 1957 it has been realized that the collision cross-section of nitrogen molecules is roughly proportional to electron velocity[15] and that this demands some modification to the original Appleton-Hartree equations for radio wave propagation in an ionized medium. The correct form of the equations has been worked out by Sen and Wyller,[16] and this is used whenever necessary in modern calculations. The appropriate collision frequency ($\nu_M$) for use in this theory is $7{\cdot}5 \times 10^5\, p$ where $p$ (in pascals, Pa; 1 Pa = 1 Nm$^{-2}$) is the atmospheric pressure.[17] As atmospheric pressure varies during the year in the mesosphere, so does the collision frequency. Values for summer and winter at mid-latitudes are given in Fig. 2.

It is still far from clear how the ionizing radiations mentioned in Section 1 give rise to the electron densities actually found in the C and D layers. After an electron and ion pair are formed an elaborate series of reactions takes place involving many neutral and ionized constituents. The concentration of many neutral species important in these reactions is very inadequately known, especially NO, O, and $H_2O$, and research is under way in various laboratories to overcome this difficulty. The ions in the D region are also being studied, and rocket measurements first showed in 1965 that below 82 km water-cluster ions such as $H^+(H_2O)_2$ are predominant,[18] contrary to the previous view that $NO^+$ and $O_2^+$ were the major ions. A review of this complex subject is given by Thomas.[19]

## 3 The E Layer

The behaviour of the normal E layer was established well before 1957, although the ionizing radiations (see Fig. 1), which act principally upon $O_2$ and $N_2$, were not measured accurately until later. The variations of electron density depend very largely upon $\chi$, the solar zenith angle, and not greatly on other factors although there is an appreciable sunspot cycle dependence.[20,21] An important feature of this layer is that electric currents flow in it

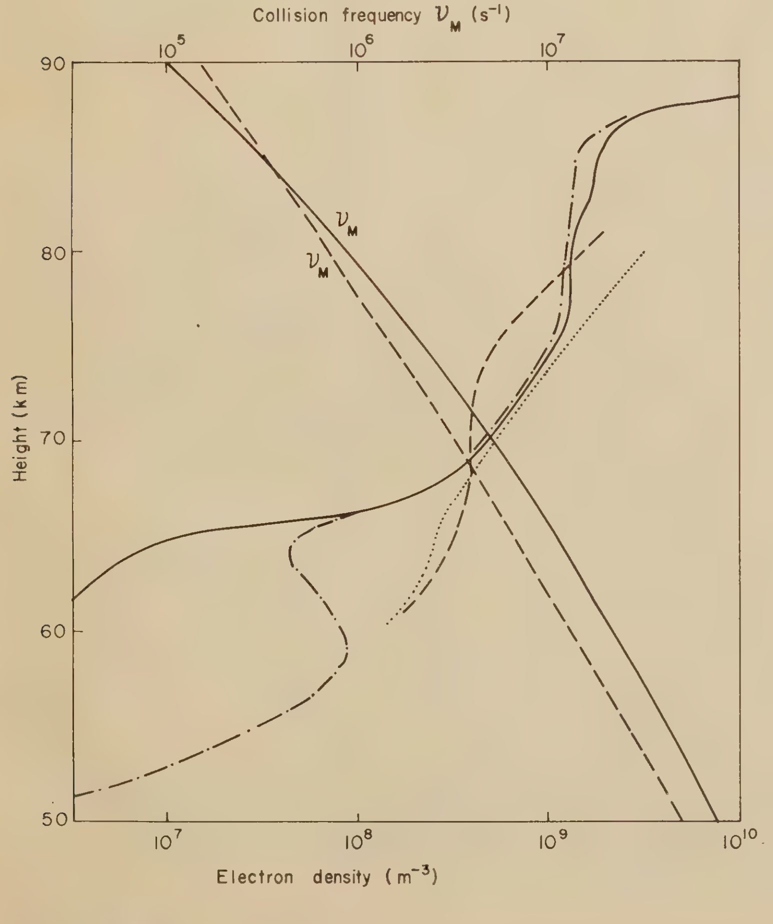


**Fig. 2.** Electron density distributions for the C and D layers produced by various methods under summer noon, sunspot maximum conditions.

——— (a) Mechtly and Smith,[7] rocket, Wallops Island, 24 July 1968.

– – – – – (b) Coyne and Belrose,[8] partial reflexion, Ottawa, May 1970.

. . . . . . (c) Barrington *et al.*,[6] wave interaction, Kjeller, summer 1960.

–.–. (d) Bain and Harrison,[9] propagation derivation, England, summer.

The curves marked $\nu_M$ show typical collision frequency distributions for latitude 52°N.

——— summer – – – – – winter

much more readily than elsewhere in the ionosphere. Variations in the magnetic field measured at the surface of the earth with periods of a day or less can be ascribed to such currents, which are produced by the so-called atmospheric dynamo effect. The dynamo functions because winds blowing in the E layer cause ions and electrons to move in different directions, so that electric currents flow.[22]

Thin ionized layers with a maximum electron density greater than that of normal E are often found between 90 and 150 km, and are given the name of sporadic E (or Es) because of the variability in time and space of their occurrence. They are much less well understood than normal E; some progress has been made but a great deal remains to be done. Sporadic E is a complex phenomenon, with different behaviour at low, middle, and high latitudes and no one cause seems able to account for all its vagaries. Because of its often high critical frequency it is of considerable practical importance, and can at times take over propagation from the F2 layer or can cause serious mutual interference, e.g. between television services in the lower v.h.f. band.

Near the magnetic equator sporadic E is found over the narrow range of $\pm 5°$ in magnetic dip and occurs in daylight at all seasons, often reaching a critical frequency of 10 MHz.[23] It appears to be associated with the equatorial electrojet, a strong electric current located in the E layer. At mid-latitudes sporadic E most commonly occurs in the summer and exhibits a different diurnal variation. Here the principal cause of the layer may be a rapid variation with height in the speed of the neutral wind.[24] Finally at high latitudes sporadic E is detected most frequently at night and is believed to be produced by auroral electrons incident on the ionosphere from above.

## 4 The F Layer

From the practical point of view the F layer is the most useful part of the ionosphere, and from the scientific point of view it has provided some of the hardest puzzles. At night it is the only part of the ionosphere that can regularly be used for communications (there are sometimes dense Es layers but these are scarcely reliable). By day the F layer is sometimes split into components called F1 and F2; the former is not very prominent on $N(h)$ profiles, such as that of Fig. 1, but it does often produce a well-marked critical frequency on ionograms. When the F1 layer does appear, its critical frequency varies very

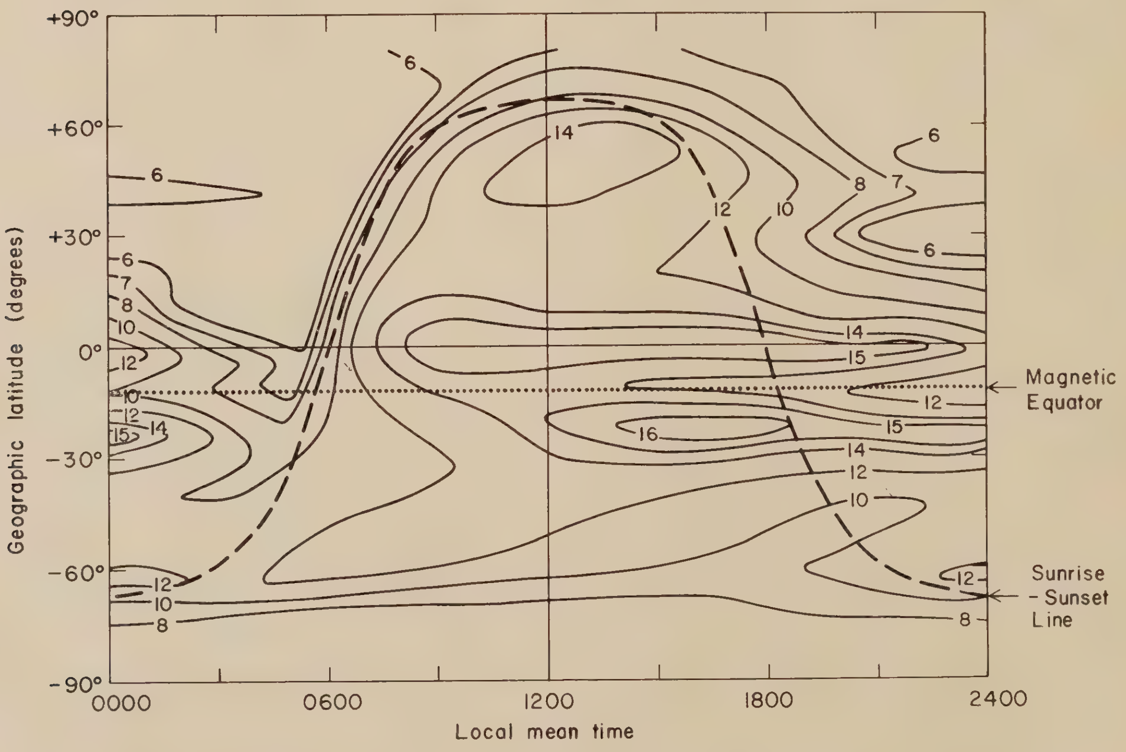


**Fig. 3.** Contours of critical frequency (in MHz) for the American zone, sunspot maximum (Dec. 1957), from CRPL Series D Predictions, US Dept. of Commerce. The chart shows the extra-ordinary critical frequency $f$xF2 which is slightly greater than the ordinary critical frequency $f$oF2 (which in turn is proportional to $\sqrt{(N m\text{F2})}$). Note the seasonal anomaly at mid-latitudes (noon critical frequency greater in the winter (northern) hemisphere than the summer (southern) hemisphere) and the equatorial trough (critical frequency smaller at the magnetic equator than at neighbouring latitudes, from before noon till after midnight).

regularly with solar zenith angle. But sometimes by day —especially in winter—and always at night, there is only the F2 layer and, as is well known, the F2 layer displays some very odd behaviour.

The first puzzle is what ionizes the F2 layer. The least penetrating ultra-violet radiations, namely those of 20-80 nm wavelength, are most strongly absorbed in the F1 layer. Above this level the rate of ion production ($q$) decreases with height, roughly in proportion to the density of the air, and is several times smaller in the F2 than in the F1 layer. Two possible reasons for the greater electron density in the F2 layer are that (i) there is an extra source of ionization or (ii) the recombination of ionization is much slower than it is at lower heights.

There is no electromagnetic ionizing radiation capable of being strongly absorbed in the F2 layer, so (i) would imply that the ionization is due to bombardment by energetic particles. This hypothesis is not generally accepted, except for some high-latitude phenomena. Alternative (ii), originally proposed in 1938,[25] fits in well to the basic theory of F region chemistry which was put forward by Bates and Massey[26] in 1946 and became quite well confirmed around 1957 when data became available from mass spectrometers flown in rockets.[27] We shall not describe this theory there, but merely note that it depends on the various chemical reactions that create and destroy positive ions and electrons, and on how the composition of the air varies with height: in the E region the air is composed mainly of $N_2$ and $O_2$, but these give place to atomic oxygen O as the main constituent at F2 layer heights. It turns out that the balance between production and loss of ionization take the forms:

$$q = \alpha N^2 \quad \text{(E and F1 layers)} \qquad \text{(a)}$$

$$q = \beta N \quad \text{(F2 layer)} \qquad \text{(b)}$$

Equation (a), with a recombination coefficient $\alpha$ that varies little with height, accounts for the nearly ideal 'Chapman layer' behaviour of the E and F1 layers.[28] Moreover, Ratcliffe[29] showed that the transition from (a) to (b) just above the F1 layer accounts for the layer being sometimes visible as a separate feature, and sometimes not. The coefficient $\beta$ in (b) depends on the abundance of $N_2$ and $O_2$ molecules, and decreases upwards faster than does the production rate $q$. This, then, is why the F2 layer has a greater electron density than F1. But it leads on to the next puzzle: why does $N$ reach a peak at around 250-350 km (the F2 peak) and then decrease?

This question was answered in the years around 1956–1960. The F2 peak is situated at a level where the air is so thin that the ionization can rapidly diffuse through it, and where production and loss become too slow to overcome the natural tendency of the ionization to settle into a gravitationally-controlled distribution, with density decreasing upwards, similar to that of the neutral air.[30,31,32] At and above the F2 peak the time taken by the ionization to settle under gravity is shorter than its lifetime, which is $\beta^{-1}$. This theory accounts for the existence of the F2 peak[33] but not for the anomalous behaviour of the peak electron density. In the next Section we briefly consider anomalies, some of which are illustrated in Fig. 3.

In time various anomalies were explained. Mostly they are produced by dynamical forces—winds, electric fields, temperature changes—and cannot be understood in terms of a purely static theory like that of equation (b). Theories of these dynamical processes made great advances in the period under review.

## 5 Anomalies and Irregularities

Among the various ionospheric anomalies, we shall mention a few that mainly concern the F2 layer:

*Seasonal anomaly* (noon *Nm*F2 at mid-latitudes greater in winter than in summer) (Fig. 3). Changes of atmospheric composition seasonally alter $q$ and $\beta$;[34] the cause of the changes is not yet certain, but is probably linked to world-wide circulation in the upper atmosphere.[35] There are also marked semiannual variations of *Nm*F2, particularly in the southern hemisphere.[36]

*Day-to-night changes of hm*F2 *and the detailed behaviour of Nm*F2 (Figs. 1 and 3). Strong winds blow at F region heights from the heated dayside to cooler nightside of the atmosphere. By driving the ionization along magnetic field lines they can raise or lower the layer,[37,38] i.e. move it to a height where $\beta$ is smaller or larger: this causes variations of *Nm*F2.

*The equatorial trough in Nm*F2 (Fig. 3).
This feature was discovered from ground-based soundings,[39,40] but satellite observations showed it to be even more prominent on the topside of the F2 layer. Martyn[41] suggested that electric fields in the low-latitude ionosphere act in such a way as to drive the ionization away from the magnetic equator and concentrate it at latitudes about 15° either side of the equator. This has since been verified by detailed theoretical calculations.[42,43]

*Small-scale structure*
Most of the ionospheric features we have described have been large-scale ones, at least hundreds of kilometres or several degrees of latitude and longitude in horizontal extent. But the ionosphere is not really as smooth as that. There are day-to-day variations of electron density, which in the F2 layer may be 20% or more; and there are localized variations from place to place, some perhaps connected with unknown local variations of atmospheric composition or temperature, and some undoubtedly connected with auroral or magnetospheric structure (Sect. 7). Some irregularities take the form of waves, notably the 'travelling ionospheric disturbances' that sometimes travel for thousands of kilometres and are largely produced in the auroral zones and in meteorological disturbances.[44,45] Even on scales of less than a kilometre the ionosphere is usually irregular: the irregularities that cause fading of radio waves are of order 100 m in size but, except for certain types, how they are produced is still not understood.[46]

## 6 Ionospheric Storms and S.I.D.s

The effects of sudden ionospheric disturbances and magnetic storms on the D region are quite profound. The best known manifestation of the s.i.d. to radio engineers is no doubt the short-wave fade-out which has long been known to be associated with solar flares.[47]

During the period under review it was finally established that the major radio effects of the s.i.d. are due to greatly enhanced ionization below about 85 km, and that this ionization is produced by hard X-rays (wavelength 0·1–1 nm) from the Sun. The intensity of these X-rays can increase by several orders of magnitude during a flare and can readily be measured by satellites. On magnetic storms, the principal development has been the demonstration by Belrose and Thomas[48] of the exact sequence of propagation changes over the frequency range from v.l.f. to h.f. due to D region disturbance.

Magnetic storms do not greatly affect the E region but produce strong effects in the F region. There may be either increases or decreases of *Nm*F2. These are due to a combination of strong winds, composition changes, and electric fields, probably caused (via a complex chain of events which is still imperfectly understood) by particles and electric currents entering the atmosphere at high latitudes.[49,50,51,52] It used to be thought that the F2 layer is raised by several hundred kilometres during storms, because of the conspicuous increases of virtual height seen on ionograms; but we now know that the changes of real height are quite small.[53]

## 7 The Magnetosphere

The Earth's outermost atmosphere has long been a topic of scientific interest, but only since 1957 has it been actively explored by satellite-borne instruments. In 1959 the term 'magnetosphere' was coined to denote the tenuous ionized region, some tens of Earth radii in size, that is permeated by the Earth's magnetic field.[54] The magnetosphere is populated by charged particles: energetic protons and electrons with keV and MeV energies and a low-energy plasma of ions and electrons that can in some ways be regarded as an extension of the ionosphere. Conversely, the ionosphere can in some ways be regarded as the innermost shell of the magnetosphere, and this relationship does influence the structure of the ionosphere at high latitudes.[55] Our account will be brief and descriptive; we cannot go into the complicated processes by which the charged particles gain or lose their energy, and indeed some of the mechanisms are still poorly understood. (For a recent review see Roederer.[56])

Out to distances of a few Earth radii, the magnetic field resembles the dipole field of an ordinary bar magnet (see Fig. 4). Beyond this, the field is distorted by the solar wind, a supersonic stream of charged particles emitted by the Sun.[57] The Earth's magnetic field presents an obstacle to the solar wind, creating a 'bow shock' rather like the 'bow wave' of an obstacle in a fast-flowing river. The solar wind flows round the Earth's field, compressing it on the upstream (day) side and dragging it out into a long tail, probably hundreds of Earth radii in length, on the downstream (night) side. There is a distinct boundary, called the 'magnetopause', between the solar wind and the magnetosphere. Charged particles from the solar wind can enter the magnetosphere and thence the ionosphere, either in the vicinity of the 'cusps' shown in the Figure or, more deviously, by entering the tail well downstream where it merges with the weak interplanetary

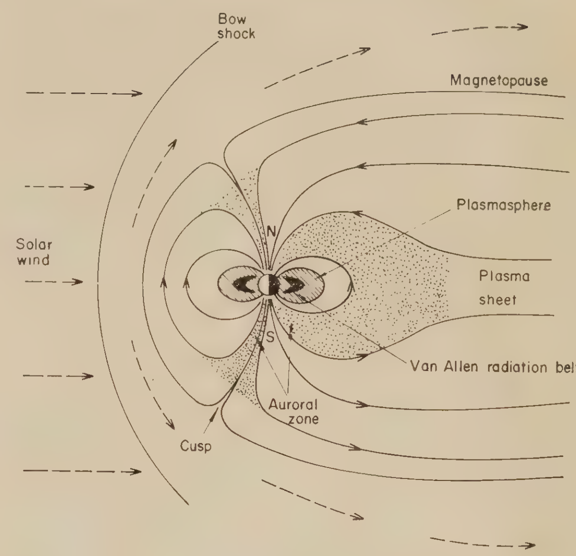


**Fig. 4.** Side-view sketch of the magnetosphere, not to scale: the Sun is on the left and the Earth at the centre: the day side is white, the night side black. The lines of force of the Earth's magnetic field are shown as fine curves issuing from the South Pole and entering the North Pole. The black crescents show approximate positions of the Van Allen belts; the shading shows the relatively dense region called the plasmasphere; and the stippling shows the regions populated by energetic particles that cause aurora when they are precipitated into the auroral zones. Broken arrows indicate the flow of solar wind outside the magnetopause.

magnetic field and returning towards the Earth. We should remark that the configuration shown in Fig. 4 is not universally accepted: for instance, some theories picture the magnetic field lines at high latitudes as being directly linked through the magnetopause to the interplanetary field.[58]

Inside the magnetosphere is a zone (stippled in Fig. 4) which contains the charged particles that cause auroral displays when they are precipitated into the atmosphere in the auroral zones.[59] Certain characteristic types of sporadic E and enhanced D layer ionization also occur in the auroral zones. Typically the precipitated particles are electrons of 10–100 keV energy, and they very probably gain their energy from electric fields in a region of weak magnetic field within the 'plasma sheet'. Closer in are the Van Allen radiation belts, containing particles of up to MeV energies trapped in the Earth's magnetic field:[60] although these particles are continually lost by precipitation into the atmosphere (and of course are replenished from various sources), they do not seem to produce particularly marked effects in the ionosphere.

As for the low energy plasma, it is interesting that the first measurements of electron density in the magnetosphere came from quite simple radio equipment at ground level. Storey[61] studied the natural v.l.f. signals called 'whistlers' that originate in lightning flashes and travel along the Earth's magnetic lines of force in what we now call the magnetosphere, their propagation characteristics depending on the magnetospheric electron density. This work eventually led to the discovery of a doughnut-shaped region, the 'plasmasphere' (shaded in Fig. 4),

in which the plasma is relatively dense.[62] The plasmasphere probably acts as a reservoir for the mid-latitude F2 layer, gaining plasma by day and helping to maintain the F2 layer at night by a return downward flow.[63] At the plasmasphere's outer boundary, the 'plasmapause', the electron density drops sharply. A corresponding feature can be seen in the topside ionosphere, too, at heights of several hundred kilometres: it forms the low-latitude edge of a 'trough' which is bounded on the poleward side by the auroral zone.[64,65,66] It has been suggested that the plasmapause is the outer limit of the region that co-rotates with the Earth;[67] and it is believed that the plasma on higher-latitude field lines is depleted by the 'polar wind', a streaming of plasma from the ionosphere along field lines into the tail and perhaps ultimately to interplanetary space.[68] However, we must caution readers that the relationships between the plasmapause, trough, polar wind, etc. are probably a good deal more complicated than our brief description might suggest.

Following disturbances on the Sun, the solar wind becomes intensified and there results a complex chain of events that profoundly affects the magnetosphere and ionosphere. This is a magnetic storm. One manifestation of a storm is a temporary shift to lower latitudes of the auroral zone and the plasmapause.[59,63,66] The input of charged particles to the atmosphere increases, strong electric currents flow in the auroral zones, and the resulting input of energy heats the upper atmosphere, modifies the winds, and indirectly causes the ionospheric storm phenomena that were touched upon in Section 6.

## 8 Conclusion

We have described some of the ways in which the Earth's environment has been explored since 1957. The exploring has been done, not only with rockets, satellites and radar, but also with the pencils, paper and computers of the theorists who have developed many new ideas. As a result, we can say that the physics and chemistry of the processes that control the ionosphere's behaviour are quite well understood. To a lesser extent this is true of the magnetosphere.

Over the years a rather fundamental change has taken place in ionospheric science. If one excludes its radio propagation aspect (which we have not been much concerned with in this paper), one might say that ionospheric science has practically ceased to exist as a separate entity: it has rightly become a branch of upper atmosphere science in general, for which the term 'aeronomy' has been adopted. This is because the full study of most ionospheric problems requires data on neutral atmosphere structure and motions, magnetic field variations, optical airglow emissions, solar radiations, and other factors that are not ionospheric. Much of the work we have mentioned has been made possible by the availability of these kinds of data.

We must however admit that we cannot fully explain, and much less predict, much of the detailed structure of the ionosphere. Probably the finer details will never be completely and quantitatively explained. Among the major problems that still remain are some important aspects of D region chemistry, the formation of various kinds of small-scale irregularities, and the complicated topic of ionospheric storms. Even so, progress in these areas continues.

## 9 Acknowledgment

This paper is published by permission of the Director of the Appleton Laboratory of the Science Research Council.

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*Manuscript first received by the Institution on 1st May 1974 and in final form on 15th July 1974* (*Paper No. 1619/Com*)

UDC 551.510.535:523.74/5

# Solar-terrestrial relations and short-term ionospheric forecasting

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and

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**SUMMARY**

Since the ionosphere is produced by the quiet Sun and disturbed by the active Sun, short-term ionospheric forecasting is discussed in three stages:

(1) forecasting the solar activity;

(2) the relations between the solar activity and geophysical disturbances, particularly magnetic storms, daylight fadeouts and polar cap absorption;

(3) the effects of these geophysical disturbances on the ionosphere and on ionospheric radio communications.

A short history of the subject is given, the international arrangements for collecting and rapidly exchanging the required solar and geophysical data are outlined, and short-term forecasting services at present operating are described briefly.

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**Table of Contents**



## 1 Introduction

Ionospheric forecasting has been defined by Meek[1] as 'the process leading to foretelling the state of the ionosphere for a specified future time at a specified point and estimating its effect on the operability of a given communications circuit'. For short-term forecasting, the specified future time is taken to be a few hours to a few days in advance, although in the years nearing sunspot minimum forecasts may also be made a solar rotation (about 27 days) ahead. It has long been known[2] that the effects at specific points and on given radio circuits depend on the intensity-time patterns and on the local times of commencement of geophysical disturbances affecting the ionosphere, so that very specific forecasts must await the start of a disturbance and can be updated as it proceeds.

Geophysical disturbances have generally been measured and compared in terms of the accompanying geomagnetic disturbances, and the story of short-term forecasting is very largely the story of the relations between magnetic storms and solar activity, but the

day-to-day fluctuations related in part to short-term changes in the Sun's ionizing radiation rather than to particular disturbances are now receiving more attention. Daylight fadeouts and polar cap blackouts are also included in the general term Solar-Terrestrial Relations and will be discussed separately in this paper.

Obayashi[3] and Egeland[4] have published comprehensive reviews of solar-terrestrial relations while Chapman and Bartels[5] gave a complete history of the subject from earliest times to 1940: this history is carried through to 1969 by Akasofu and Chapman.[6] Shorter reviews are to be found in many textbooks on the ionosphere and the Sun, for example by Mitra[7] and Newton,[8] and others with accompanying descriptions of short-term forecasting systems in use have been given by Shapley,[9] Kojan and Isted,[10] Bennington and Prechner,[11] Cook,[12] Moore,[13] Piggott and Allen,[14] Fokker and Roosen[16] and Zevakina *et al.*[17]; and by Lincoln,[18] Beckmann[19] and Stonehocker[20] in AGARD Conference Proceedings No. 49 which contains much other information on current forecasting techniques and systems and users' requirements, and discussions on whether forecasts should be made at all. A useful summary of the state of the art is given also in the IUWDS booklet[21] describing the international arrangements for collection and rapid exchange of solar/geophysical data for scientific and communications purposes.

No attempt will be made in this paper to cover this wide field in detail. We hope nevertheless to give a connected, if incomplete, account of how short-term forecasting has been developed from the study of solar-terrestrial relations and its application to current problems.

## 2 Forecasting the Solar Activity

There are two aspects to the problem of forecasting solar activity as distinct from forecasting the effects of activity once it has been observed. Firstly, since the Sun's ionizing radiation consists of a steady part, and a part coming from localized active regions on the Sun and varying with the level of solar activity as given by sunspot number, microwave radio flux and other measures, then forecasts of day-to-day fluctuations in this level might enable us to forecast related fluctuations in ionospheric usable frequencies. Secondly, it would be useful to be able to forecast solar events, particularly major flares which cause fadeouts and in many (but not all) cases magnetic storms.

### 2.1 General Level of Activity

Correlation between ionospheric E, F1 and F2 critical frequencies on the one hand, and sunspot numbers, areas of bright hydrogen and calcium flocculi and the relative amplitude of the geomagnetic Sq field (which in turn relates to ionization in the E region since that is where the Sq currents flow) was found by Allen,[22] using monthly mean values of these parameters. No conclusions could be drawn about shorter term relations, nor would any be expected because of ionospheric fluctuations caused by non-solar factors such as atmospheric turbulence, winds, migration of electrons and ions along the Earth's field lines, and the large variability in sunspot number from day to day especially at low sunspot number. (Sunspot number is given by $K(10G+S)$ where $G$ is the number of spot groups on the visible disk, $S$ is the number of spots making up these groups, and $K$ is an observational factor near unity. This quantity can easily vary from zero to say 30 or 40 and back to zero in three or four days.) Similarly, Kundu and Denisse[23] found close correlation between E-region ionization and flux density of solar radiation at 10·7 cm using 5-day means. They chose 10·7 cm because a long and consistent sequence of data exists for this wavelength,[24] which also happens to be very near the wavelength at which the slowly-varying component is a maximum.[25]

These and similar studies have little application, however, to the forecasting of particular disturbances a few days ahead, although they do help in establishing trends when taken in conjunction with other indicators of likely magnetic disturbances as will be seen later, and we still need to forecast the activity level. To do this we need to look at the active regions on the Sun.

### 2.2 Evolution of Active Regions, and Solar Events

There is some evidence that solar activity tends to be concentrated in certain preferred ranges of longitude on the Sun. This is discussed by Dodson-Prince and Hedeman[26] for solar activity 1962–1966 which tended to occur in two zones on opposite sides of the Sun, and for proton flares 1954–1963 by Warwick.[27] The subject is reviewed by Bumba[28] who refers also to large-scale structure in the solar wind which sweeps past the Earth with the Sun's rotation and which we will discuss later in the Sections on recurrent magnetic storms and solar wind structure. For short-term purposes we take this a

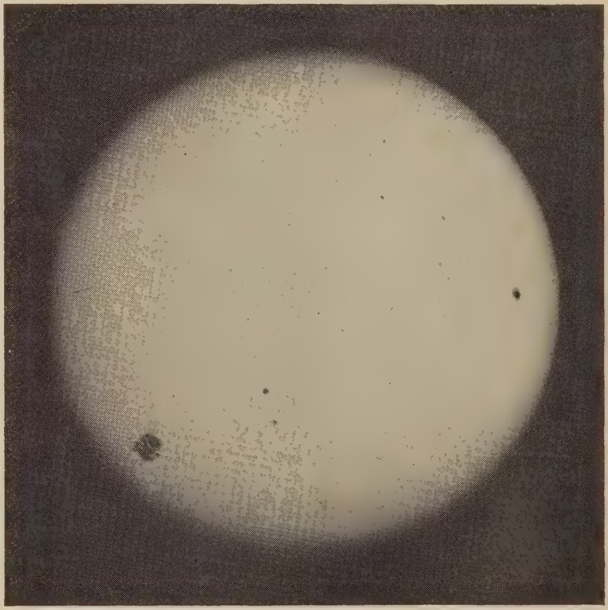

**Fig. 1.** The Sun in white light, showing spot groups. Culgoora Observatory. (*Photo: CSIRO National Measurement Laboratory.*)

step further and consider the active regions separately, the obvious active region indicator being the sunspot group (Fig. 1).

From the immense volume of information about sunspots and flares we note that about 20% of the spot groups produce 80% of the flares.[29] Flares tend to occur mainly in the first ten days or so of the life of a spot group so there is a general relation between flare occurrence and both area and complexity as observed in white light,[30] and with magnetic complexity according to line-of-sight measurements of the spot magnetic fields.[31] These points are discussed further by Bray and Loughhead in their study of sunspots.[32] Magnetic complexity implies the existence of neutral lines between areas of opposite magnetic polarity, and magnetic gradients perpendicular to these lines. Severny[33] found that most flares start near a neutral line and that the threshold gradient for major flares (i.e. flares which might by expected to produce significant fadeouts) is about 0·1 gauss/km, so it would be useful to find visual or radio methods of identifying such likely flare sites. Caroubalos and Martres[34] introduced a parameter $d/D$ where $d$ is the distance between the near edges of two spots or groups of spots of opposite magnetic polarity and $D$ is a measure of the spot areas. A low value of $d/D$ indicates small separation of the spots and presumably a steep magnetic gradient between them. Avignon *et al.*[35] used this parameter to show that regions with low $d/D$ are associated with high centimetric wave flux, and according to Tanaka and Kakinuma[36] most proton flares (which are usually major flares causing severe fadeouts) occur in regions where the ratio of flux densities at 3·2 cm and 7·8 cm is greater than one. More recently, Martres *et al.*[37] have related flare occurrence to pairs of 'evolving magnetic features', one of which is found to be increasing in either area or magnetic flux and the other decreasing.

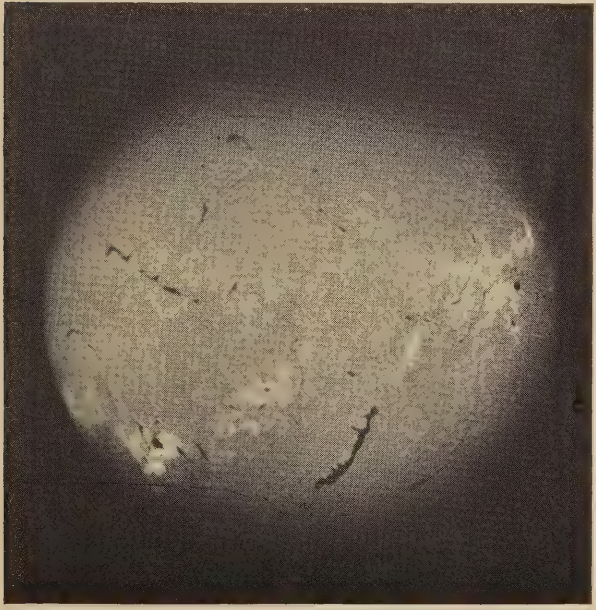

**Fig. 2.** The Sun in H-alpha (at the same time as in Fig. 1) showing spots, bright plages, filaments, and granulation. Culgoora Observatory. (*Photo: CSIRO National Measurement Laboratory.*)

Leighton[38] showed that solar magnetic field regions coincide with the calcium plage areas, which are observed photographically in ultra-violet light. McIntosh[39] has developed techniques for inferring magnetic fields and presence of neutral lines from visual H-alpha observations (Fig. 2) of five kinds of chromospheric structure (filaments, fibrils, filament channels, arch-filament systems, and plage corridors), and in detailed comparison with the Mt. Wilson solar magnetograms during a two-month period in 1970 claims 93% agreement between measured and inferred polarities of regions.[40] Some disagreement is to be expected because of the difficulty of measuring fields near the solar limb, i.e. at large angles to the line of sight.

Another lead to active regions is the observation, close to the Sun's limb, of intensities of the coronal emission lines, mainly the green line $\lambda$5303 (Fe IV) and yellow $\lambda$5694 (Ca XV), which are enhanced above centres of activity. Unfortunately we can observe these lines only as the regions appear at the east limb or disappear at the west, seven days before or after central meridian passage (c.m.p.). It would be convenient if we could observe the corona at central meridian, opposite the Earth, from a spacecraft in orbit round the Sun at 90° from the Earth,[41] but until this can be done we take the intensity at c.m.p. to be the mean of the observed values at e.l.p. and w.l.p.

Regions thus observed to have complex sunspot and magnetic field structure with strong centimetric-wave radio emission, steep field gradients, and enhanced coronal emission are identified as promising producers of flares, though another study by de Peralta and Billings[42] of 486 flares in 18 regions in July/August 1967 relates flare productivity to the lengths of the neutral lines, not to magnetic field gradients, or areas, and they list one exceptionally productive region which had simple bipolar structure and only moderate field gradients. Identification of likely flare sites enables us to make short-term predictions of the likelihood of flares and hence radio fadeouts, but we still cannot say exactly when a flare will occur as the triggering process is still not understood.[43] This process may well depend on activity in another part of the solar disk, since heliograph observations[44] show distant centres to be linked magnetically.

The paper by Pick and Simon[43] details the present status of flare forecasting and describes its application to current problems, while a survey of the theoretical and observational background and practical application is given in 'Solar Activity Observations and Predictions' (McIntosh and Dryer, Eds.).[45] The editors, in their preface to this volume, state 'Predicting solar activity is so difficult that some knowledgeable people have concluded that it may be impossible'. Simon and McIntosh[46] claim about 80% accuracy for the Meudon and Boulder forecasts of events on a daily basis, with greater accuracy for the major events. For ionospheric storm forecasts, we must still wait on the event since we do not know at what time during the following day it will occur (if

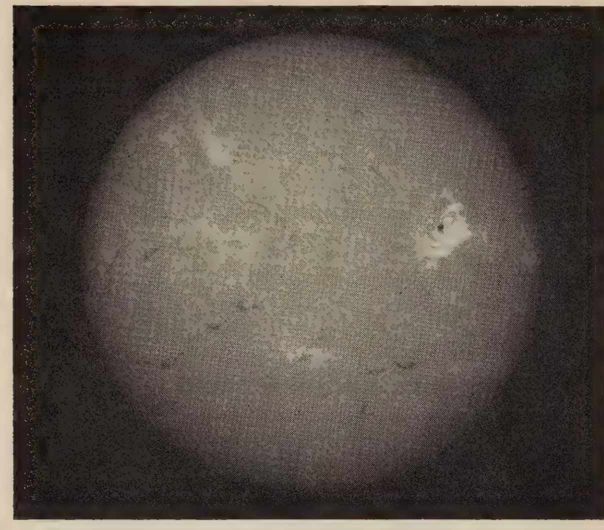

Fig. 3. A large solar flare on 31 October 1968. (*Photo: Solar Particle Alert Network Observatory, Carnarvon, W.A.*)

it does occur), or what kind of flare it will be (storm-producing or not) until it has been observed at both optical and radio wavelengths.

## 3 Solar Flares and Sudden Ionospheric Disturbances

A radio fadeout or sudden ionospheric disturbance (s.i.d., also called Mögel-Dellinger effect,[47,48] or short-wave fadeout, s.w.f.)[49] is a partial or complete absorption of radio signals via the E and F regions on the sunlit side of the Earth, due to excess ionization in the D region produced by X-radiation from a solar flare (Fig. 3), the effect falling off rapidly for solar zenith angle of more than about 50°.[50] It may also be observed as an enhancement of atmospherics on long waves (s.e.a.),[51] a sudden phase anomaly (s.p.a.)[52,53] on long waves, a sudden cosmic noise absorption[54] in which radiation from space reaching the Earth through the whole ionosphere suffers some absorption, or a sudden frequency deviation (s.f.d.).[55]

The problem of forecasting s.i.d.s is the same as that of forecasting flares, discussed in Section 2.2 of this paper. Almost all flares have some detectable effect on the ionosphere, but only the major ones are of interest to radio communicators at the times of their occurrence. Their main interest to forecasters is in their role as possible precursors of magnetic storms.

A review of the literature on s.i.d.s to 1960 is given by Collins.[56]

## 4 Proton Events and Polar Cap Absorption

The occurrence of radio wave absorption at high latitudes in spiral loci centred on the geomagnetic poles has been studied for many years in connexion with magnetic storms and high-latitude radio propagation. Nikol'skii[57] for example reported that 'The occurrence of this type of absorption is associated, in a considerable fraction of the cases, with a simultaneous occurrence of magnetic disturbance. This has given reason to suppose that the cause of these absorptions is a penetration of solar corpuscles into the upper strata of the terrestrial atmosphere.' The great solar-terrestrial event of 23rd February 1956 focused attention, however, on a new phenomenon, similar in effect to an s.i.d. but observed in the dark hemisphere and beginning some 10–20 minutes after flare start which was at 0332 UT on that day, and confined to the polar cap until the magnetic storm began about 47 hours later. On the sunlit hemisphere a very severe and long-lasting s.i.d. was observed at the same time as the flare. Shapley and Knecht[58] summarized the ionospheric and other observations made at this time, which included a ground-level cosmic ray increase such as occurs only a few times in a complete solar cycle.

The ionospheric data used here were the vertical-incidence observations of $f$ min, which were used also by Hakura *et al.*[59] in investigating the severe storms of September 1957 and February 1958; they clearly showed blackouts starting in the polar regions about 31 h and 9 h after the flares are believed to have been responsible, extending to lower latitudes following the magnetic storm commencements 15 h and 19 h respectively after that. Hakura and Goh[60] then examined the IGY data and found a striking correlation (but not complete correlation) between these pre-SC blackouts and the occurrence of solar radio type IV bursts at metric, decimetric and centimetric wavelengths at the times of the corresponding flares, while Kundu and Haddock[61] related polar cap absorptions (p.c.a.) to broadband centimetric wave outbursts, with shorter delay times for more intense outbursts. (For details of solar radio emissions and burst types, which will not be discussed here, see, e.g., the review by Wild, Smerd and Weiss.[62,63])

These studies were extended by many other workers who found that p.c.a.s are more common than was thought previously[64] (since earlier methods of observation detected only the major events), that they tend to favour flares on the western half of the Sun's disk,[65] and that particles from 'western' flares tend to arrive more quickly.[66] From all these papers emerged a close correlation between p.c.a. and the occurrence of a magnetic storm later.

Since the particles causing p.c.a.s may be energetic enough to be a hazard to space travellers, besides blacking out polar h.f. radio and relating to magnetic storms, much effort has been directed to identifying the kinds of flares which produce them and the kinds of solar regions in which they occur, and to predicting the delay times between flare and p.c.a., and the intensities of the events. NASA Technical Report TR R-169[67] discussed the cosmic ray aspects and described 13 p.c.a.-producing regions, and Technical Note TN-D700[68] related 38 out of 40 events (expected number, 27) to large penumbral area of the associated sunspot groups. Sinno,[69] from study of 33 events in 1956–1959, identified two kinds of p.c.a. according to their delay times; one with delay of a few hours from flare time (having travelled possibly direct from Sun to Earth) and one delayed until about ten hours before the magnetic

storm (possibly having been trapped in the slower-moving cloud of magnetic storm particles). He also related the fast events to flares with short delay between onset of radio bursts at successively lower frequencies, and the slow events to longer delays, although the relations are not clear-cut and have been challenged by Warwick[70] on the grounds that assignment of a specific flare to a particular p.c.a. may not be correct. Warwick and Haurwitz[71] had found no significant relation between either p.c.a. occurrence or delay time and solar longitude of the flare, but that delay time tends to be short near sunspot minimum and long near sunspot maximum, while major p.c.a.s have two maxima of occurrence either side of spot maximum.[72] A detailed review of this field up to 1963 was given by Bailey.[73]

Again, from a large volume of information, we note the following developments since that time which relate to the prediction aspects, some of which have already been discussed in Section 2.2 of this paper. Optical and magnetic field complexity of the regions has been mentioned.[30–32] Warwick[74] states that practically all energetic proton flares occur in spot groups with delta-configuration, that is with sunspot umbrae of opposite magnetic polarity close together in the same penumbra which would imply steep magnetic field gradients between them. Other workers notably Sakurai[75] confirm the need for large gradients and complexity, attained in this case by rotation of the spot groups. The radio emission criterion of Tanaka and Kakinuma has also been mentioned.[36]

Coming now to the flares, Křivský[76] in studying 'fast' p.c.a.s, i.e. delay time 2–20 minutes, found that they all showed a Y-shaped stage in which the flare begins as parallel bright ribbons either side of the neutral line, which then move apart, before the brightness maximum is reached. He discussed this further in a review paper,[77] in which he suggests that flares sometimes observed in white light at this stage indicate that protons as well as electrons are accelerated out of the flare region. The moving ribbons would be expected to move over and cover the spot umbrae, as has been remarked upon by others. Castelli *et al.*[78] examined the flare radio burst spectra of proton and non-proton flares and found that proton flare bursts gave high flux densities at metric and centimetric wavelengths with minima in the decimetre region—the so-called U-shaped spectrum, noting that corrections have to be made to the higher-frequency fluxes for flares located away from the central part of the Sun's disk. More recently Croom[79, 80] working at millimetre wavelengths (19 GHz) has developed criteria for indicating proton events and p.c.a.s, namely that at 19 GHz the peak flux increase should be more than 50% of the pre-burst value, and the flux enhancement more than 10% above it for longer than 5 minutes. Finally, McLean *et al.*[81] have given an explanation for a series of sharp pulses observed at about 2·5 s intervals in the frequency range 100–200 MHz, when the accompanying type II burst had drifted down to about 30 MHz, corresponding to a height of 1·5 solar radius above the Sun. Of eight such events examined, four were associated with proton events, one was possibly associated and in two cases the flare occurred at 55 and 56 degrees east of the Sun's centre—which makes it unlikely that any protons from these two events would have reached the Earth.

Unfortunately, while we thus have a wealth of information on probability of occurrence of p.c.a.s following the right flares in the right regions, we still have only vague leads to the delay times, other than the successive times of occurrence of the radio bursts at different frequencies, and the general observation that the more intense radio events are associated with shorter delays. Much information surrounding a few selected events (observed during times of Proton Alert based on development of the 'right regions') is given in the reports on the two Proton Flare Projects conducted in the past few years,[82, 83] and by Bryant *et al.*[84] who mention also the occurrence of magnetic storms following central meridian passage of regions which produced proton events during a previous solar rotation.

## 5 Sunspots, Flares, and Magnetic Storms

Short-term forecasting of the major magnetic and ionospheric storms is based largely upon the solar-terrestrial relationships discussed here and in the preceding Section on p.c.a. events. As with p.c.a.s we consider the active regions, and the events which occur in these regions, the occurrence of an event being marked usually by an s.i.d. It is not possible to touch on every aspect in the space available; much more, especially of the early history, will be found in some of the reviews mentioned in the Introduction to this paper.

### 5.1 Sporadic and Recurrent Storms and Sunspots

Maunder[85, 86] in two papers in 1904–1905 showed that great magnetic storms were associated with large sunspots located about one day past the Sun's central meridian at storm commencement time, and that for all storms there was a tendency to recurrence at intervals of about 27 days which is the Sun's rotation period as seen from the Earth. Greaves and Newton[87, 88] in 1928 confirmed Maunder's conclusions from many more data, showing that intense storms were associated with large sunspots, began with sudden commencements (s.c.s), and did not show a recurrence tendency, while the weaker storms showed no relation in general with sunspots, began gradually, lasted longer, and tended to recur after 27 days. These recurrent storms will be discussed later in Section 7. Some large spots, it should be noted, were not followed by magnetic disturbance.

### 5.2 The Superposed-epoch Method of Investigation

A paper by Chree and Stagg[89] is referenced so often in solar-terrestrial papers that their superposed-epoch method should be described briefly. They took the daily magnetic character figures (0·0 quiet to 2·0 very disturbed) for 1906 to 1925. Each time a particular value, 0·5 say occurred, it was placed on day 0 on a time scale, and the values on successive days entered along the scale. The sum of the values at day 0 was called the 'primary pulse', and the sums for all the other days along the

scale were examined to see if there was a 'secondary pulse', and so on for all the primary values 0·0 to 2·0. They found secondary pulses 27·0 d later for disturbed days, and 27·09 d for quiet days. Many other workers have used this method with zero on the time scale being the time of occurrence of certain kinds of solar flares, or the central meridian passage (c.m.p.) of sunspots with certain characteristics, or other phenomena.

### 5.3 Solar Flares (Optical)

The story of solar flares and magnetic storms begins in 1859 when Carrington[90] and Hodgson[91] on 1st September observed in white light what was probably an intense proton flare in a large spot group near the centre of the Sun's disk. (Carrington's sketch is reproduced on page 334 of Chapman and Bartels.[5]) The Kew magnetometer registered a crochet, which we now know accompanies a major flare and s.i.d., and about 17 h later a great magnetic storm began. Carrington knew about this storm, but an editorial note appended to his Report of the solar event in the Royal Astronomical Society's *Proceedings* says 'he would not have it supposed that he even leans towards hastily connecting them'. White light (photospheric) flares are very rare, and observations of chromospheric flares in the hydrogen H-alpha line had to await the development of the spectrohelioscope in 1931.

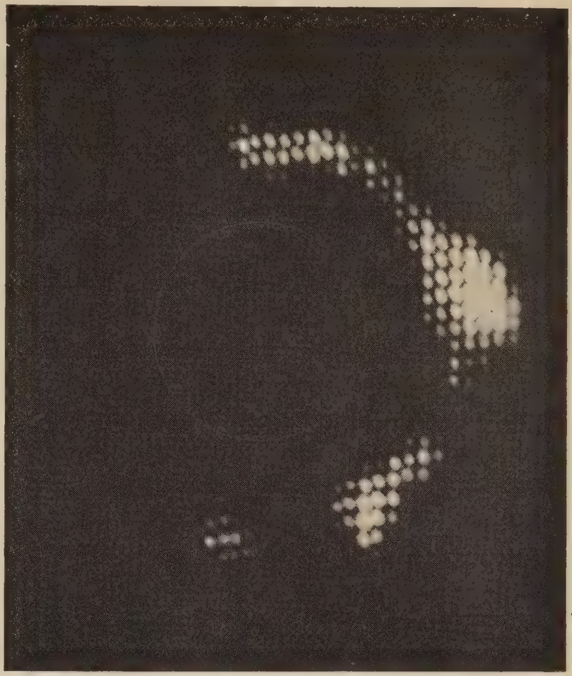

**Fig. 5.** 80 MHz radioheliogram, 30 March 1969. The flare occurred on the far side of the Sun, giving rise to a shock front which generated radio bursts as it enveloped half the Sun. (*Photo: CSIRO Division of Radiophysics.*)

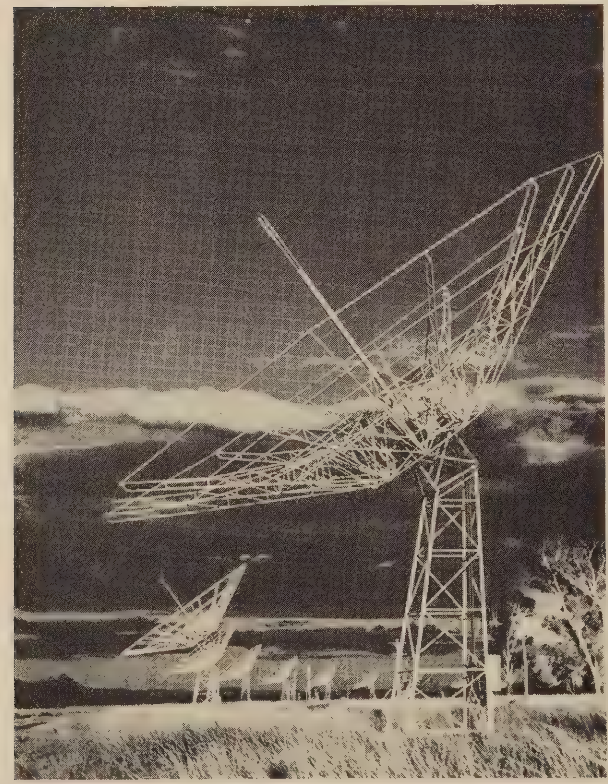

**Fig. 4.** Some of the 96 aerials of the Culgoora radioheliograph. (*Photo: CSIRO Division of Radiophysics.*)

Flares are classified in increasing importance from 1− to 3+ (see discussion in Smith and Smith's standard text[92]). Newton[93] in 1943 concluded that 80% of 3+ flares occurring in the central half of the Sun's disk are followed by great magnetic storms with a mean delay of about 26 h. A later study[94] showed a small statistical rise in geomagnetic activity following class 3 flares, and no perceptible rise after smaller ones, and again it should be noted that one in five of the 3+ flares, which are exceptional events, was not followed by any magnetic storm, a result in line with that already mentioned for some large sunspot groups.

This lack of correspondence between solar flares and magnetic storms is clearly shown if we leap forward to the well-documented eighteen months of the International Geophysical Year (IGY) 1957–1958. The McMath–Hulbert Working List of flares for that period[95] lists seven class 3+ flares, 32 class 3, 435 class 2 (including one which is believed to have caused the great magnetic storm of February 1958), and more than 6000 lesser flares. Yet there were only 22 major magnetic storms, and 23 p.c.a. events, a result which was already foreshadowed in Newton's 1943 paper. Identification of the uncommon storm-producing flares had to await the discovery of solar radio emission.

### 5.4 Solar Flares (Radio)

If a flare (or some other agency) on the Sun is to produce a magnetic storm at the Earth, particles must be

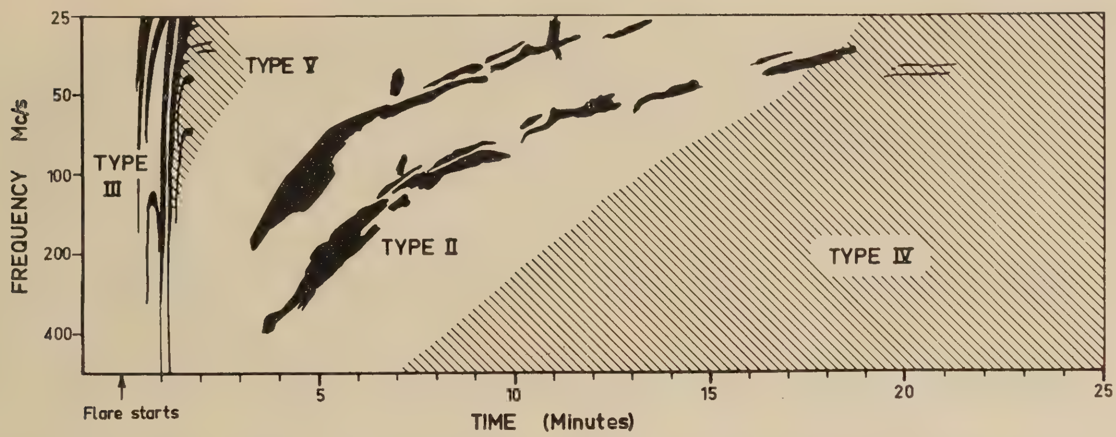


**Fig. 6.** Solar radio bursts (schematic). (*Diagram: CSIRO Division of Radiophysics.*)

ejected from the Sun. Solar radio emission might then be expected to help in identifying suitable acceleration processes as they occur, and enable us to trace the particles' progress out through the corona either by their excitation of radiation at successively lower frequencies, or by radiation from the magnetic storm clouds themselves.

Metre-wave radiation from spots and flares on the Sun was observed in Britain during World War II and reported by Hey[96] in 1946. Wild[97] in 1950 showed, in the 70 to 130 MHz spectrum of flare-associated radio events, a frequency drift from higher to lower frequencies consistent with outwards motion of the source at speeds comparable with that inferred from Sun–Earth travel times of magnetic storm particles, as had been shown by Payne-Scott *et al.*[98] from single-frequency observations at 200, 100 and 60 MHz. Particle clouds were later tracked in one dimension at 97 MHz as they moved across the Sun's disk,[99] and more recently in two dimensions by radioheliograph observations of ejected material,[100,101] although these particular events might not necessarily have been strong enough to cause significant magnetic disturbances had they hit the Earth (Figs. 5, 6). Attempts had been made to track these clouds by other means, e.g. by measuring absorption in solar spectral lines as the cloud reached the Earth[102] but these proved inconclusive, and forecasting progress now depended on understanding the significance of the types of events revealed by the radio spectrograph,[103] identification of their single-frequency equivalents (since only one spectrograph existed at that time and forecasting requires 24-h solar coverage), their extension to higher frequency ranges, and the association of all these events with flares and magnetic storms.

Wild and McCready in 1950[103] described three kinds of bursts: Type I confined to a narrow frequency band but continuing for days at a time, Type III or very fast-drift bursts, and Type II or the slow-drift burst mentioned earlier in this Section, which comes from the shock front ahead of a magnetic storm cloud pushing through the corona (Fig. 6). Boischot in 1957[104] described metre-wave Type IV, a stable wide-band emission occurring after flares and Type II, associated with solar cosmic rays;[105] some kinds of Type IV are now believed to originate in the storm clouds themselves. The full range of radio spectral events which can accompany a major flare was described by Wild (the 'Kyoto Type IV')[106] and is further discussed in the reviews by Wild *et al.*[62,63] and Takakura.[107] The single-frequency equivalent of a Type II–IV event is a short intense burst lasting typically a few minutes, before the optical flare reaches maximum intensity, followed by a smooth rise and fall lasting an hour or so, and the association of these events with magnetic storms proved to be a valuable forecasting aid (Fig. 7).

Dodson *et al.*[108] during 1948–1950 classified the 200 MHz events accompanying 151 out of 194 observed flares into ten categories, including 'major burst with second part' and suggested that 'early' burst-type events might be associated with ejection of particles. At a single frequency it is difficult to separate Type IV from a Type I storm which happens to occur at that frequency.

### 5.5 Flares in Radio-noisy and Radio-quiet Regions

While the studies of flare and bursts continued, Denisse *et al.*[109] in a superposed-epoch study of spot groups with and without 158 MHz radio emission found a significant increase in geomagnetic activity 1–2 days after c.m.p. of 'radio noise' regions, and a diminution 2–3 days after c.m.p. of quiet regions (the sources being located by interferometer and thus assigned to the spot regions). These regions became known as R and Q regions respectively. Then Becker[110] showed that c.m.p. of pairs of spots symmetrically located in the N and S hemisphere of the Sun was followed 2–3 days later by a magnetic activity minimum, and the two authors[111] then found that when both spots of the pair were Q spots, the minimum 3 days after c.m.p. was very marked, when both were R spots there was in fact a small increase, and when the R spot in Denisse's analysis was not one of a symmetrical pair, the increase was more marked and slightly delayed. Finally, Simon[112,113] pointed out that the increased geomagnetic activity found by Denisse comprised the s.c. storms (referred to in

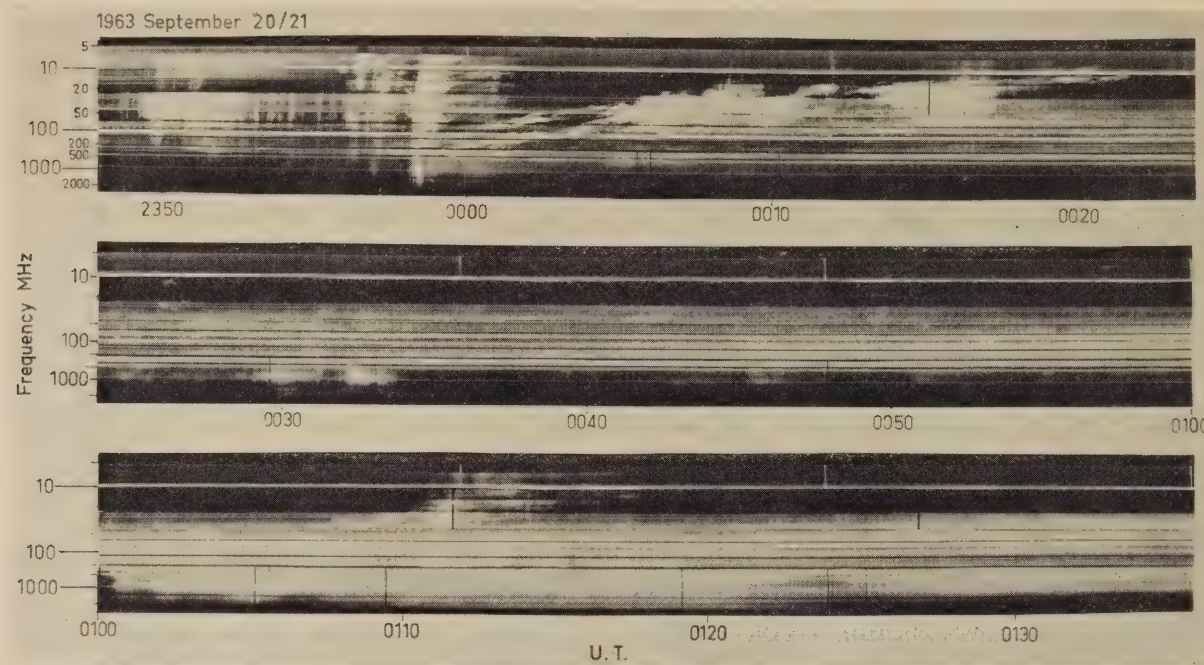


**Fig. 7.** Dynamic radio spectrum of outburst recorded between 5 and 2000 MHz. (*CSIRO Division of Radiophysics.*)

Section 5.1) not the gradual commencement storms (confirming a finding of Allen[114] in 1943), and that optically important flares in R regions tend to be followed by magnetic disturbance while equally important flares in Q regions do not, which goes part way towards explaining Newton's 1943 result that one in five 3+ flares, even in the central part of the disk, produced no storm.

### 5.6 Flares and Radio-emission Events Since 1957

The significance of events in the solar corona as shown by radio emission data was realized in time to make an impact on the IGY World Days Programme, which depended largely on forecasts of significant magnetic disturbances. A preprint of Dodson and Hedeman's paper[115] on flares with 'major early bursts' was circulated to the IGY Warning Centres in May 1957. This showed that the number of flares with major 200 MHz bursts before optical flare maximum was roughly comparable with the number of s.c. storms, these flares being a very small proportion of the total, and 68 of 115 such flares were considered to be the probable causes of magnetic storms, while important flares without such bursts were not followed by disturbance. Major flares near the Sun's central meridian tended to produce more severe storms, within this regime.

Similar evidence was presented by Sinno[116] who with Hakura[117] examined the power spectra of bursts at frequencies between 200 and 9400 MHz and concluded that outbursts with strong emission at lower frequencies and weak emission at higher frequencies, in the observed range 200 to 9400 MHz, produced magnetic storms but weak s.i.d.s, but outbursts with the reverse kind of power spectrum produced severe s.i.d.s at flare time and little or no magnetic disturbance later, with some documented exceptions, while events with flat spectra produced both s.i.d.s and storms. The first and second parts in Dodson and Hedeman's single-frequency classification were identified with Type II and Type IV spectral types, which have been described and related to the occurrence of magnetic disturbances by Roberts[118] and McLean.[119] The Dutch group also emphasized the importance of radio as well as optical observations[120,121,122] but pointed out that about half the magnetic storms could still not be related to particular radio outbursts.

The IGY 1957–58 observing programme was extended another year through the IGC (International Geophysical Co-operation) 1959. Twelve papers on solar-terrestrial relations during this period are listed by Cook.[123] Analyses by Bell[124,125,126] confirmed the radio type IV dependence, the significant factors for major s.c. storms being long burst duration, full frequency range coverage (for the data available, about 100 to 2800 MHz), and association with major flares in magnetically complex spot groups near the Sun's central meridian with, surprisingly, a northern (solar) hemisphere bias which may have been a characteristic of that solar cycle. These are also the significant factors for occurrence of p.c.a.s—the extension to gigahertz frequencies by Croom has already been noted—so that at this point Section 4 on p.c.a.s and this Section on flare-associated magnetic storms are drawn together. The detection of p.c.a.s is indeed a useful indicator of the imminence of magnetic storms.[127]

Most of these papers worked from the solar events towards the occurrence-probability of p.c.a.s and magnetic storms. Now appeared two useful papers which worked back from the magnetic storms as well, with

'case histories' of events-without-storms and storms-without-events, using the data of 1957–61. Fritzová-Švestková and Hřebík[128] confirmed the radio Type IV-storm association, but compiled six tables of major flares (F), major Type IV including those inferred from single-frequency observations (R), and magnetic storms with *K*-index 7 or more (M) where F, R or M occurred singly or with only one of the other two. Gaps in the data or arbitrariness of major/minor classification can account for some of the entries, and an occasional F-only is to be expected, as is an R-only where the flare was minor or occurred just past the Sun's limb but the radio burst from high in the corona was observed, and an FR but no M where the flare was not favourably located. Many of the M-only appear to be part of recurrent sequences (see later) but there are still unexplained storms, including major ones, which must be connected with features other than flare/radio events. Dodson and Hedeman[129] carefully examined the meanings to be attached to published data on flares and s.i.d.s, and related them to radio Type IV events, p.c.a.s and magnetic storms. They pointed out that the p.c.a. flares have occurred mainly in calcium plage areas (see Sect. 2.2 and ref. 38) in their second or later rotations across the Sun's disk, and that two very severe but 'unexplained' storms, of 5th October 1960 and 3rd September 1961 coincided with c.m.p. of regions which had produced proton flares in the preceding rotations, and suggested that 'the "maturity" of an active centre apparently is playing some part either in the ejection of high-energy particles at the time of great flares or in the arrival of particles in the neighbourhood of the Earth'. Their most recent study[130] of 294 storms in 1955–58 and 1965–68 indicates 58% apparently flare-associated, 27% probably sequential and 15% 'problems'.

The difficulty of inferring Type IV emission from single-frequency records has been mentioned: there is also the problem of different kinds of Type IV particularly that which is sometimes reported by one observatory as Type IV and by another as Type I. Weiss[131] in 1963 distinguished between stationary and moving Type IV, and three kinds of moving IV have been recognized by Smerd and Dulk[132] (see also ref. 63) who state that this is the rarest type of burst at metre wavelengths, while Akinyan *et al.*[133] describe sub-classes of moving and 'quasistationary' phases according to their particle emission mechanisms, but as far as is known relations between these types (and their intensities) and possible magnetic storm occurrence have not yet been examined. Direct observations of Type IV sources by means of the Culgoora radioheliograph may enable us to resolve this problem.

Returning now to Dodson and Hedeman's remarks on c.m.p. of proton regions from preceding rotations, Bryant *et al.*[84] list several such cases including the 28th October 1961 storm and the 1st December 1961 storm for which the 'preceding proton event' was observed by spacecraft but not as a polar cap absorption (p.c.a.) event at the Earth. The flare was a minor one at the west limb and produced no magnetic storm at the time. We will return later to this question of regions with quasi-stable streams above them.

### 5.7 Delay Times and Intensities of Magnetic Disturbances Following Solar Events

There is no lack of data on the time delays between major solar events and s.c. magnetic storms (if we accept the reality of these relationships) since both can be timed to the nearest minute: the start time of a p.c.a. is less definite (see ref. 134 for discussion of delay times from radio emission events). The many superposed-epoch studies already referred to here give a variety of mean delay times from event to storm—noting that storm maximum is some hours to perhaps a day after start time—but for any of the selected groups of data the delay between event and s.c. ranges from about one to three days, and something more precise would be desirable.

The picture of a shock front (Type II emission) pushing out through the corona ahead of a magnetic storm cloud (Type IV) and exciting emission at successively lower frequencies suggests that a frequency-time plot might give us the speed. Hartz[135] presented some measurements of an event made at a number of discrete frequencies and inferred from them a terminal velocity of about 1000 km/s corresponding to a delay time of some 40 h, and there was indeed a very short, slight s.c. disturbance 34 h later, but this method involves assumptions about the corona above active regions which are not necessarily true and other attempts to apply it have not been successful. Other interrelated studies show successively shorter delay times for a succession of flares and storms[136,137,138] as the active region moved further west on the Sun's disk, while magnetic field lines drawn out from the Sun possibly provided a more direct Sun–Earth path for later storm clouds. Another study[123] based on the IGY data suggests that for events associated with smaller calcium plage regions, the minimum delay time is greater than for comparable events in large plages, the delays again ranging from one to three days.

Caroubalos,[139] using 1958–60 data, considered the optical and radio (Type IV) importance of flares, and for optical importance she found the mean delay time to be less for large bright flares (1·9 days for flares class 3 and 3+, 2·8 days for flares 1 and 1+), but in each case there was a wide spread of values, from 1·1 to 3·6 days for example for the largest flares. The radio importance she derived from the product of maximum Type IV flux at 3000 MHz and duration of burst, obtaining once again a range of 1 to 3 days with uncertainty of about 8 hours for the shortest-delay storms and about 24 hours for the longest-delay.

Recently Pintér[140] has related the velocities computed from Type II bursts in the corona with velocities of the corresponding interplanetary shock waves measured at the spacecraft *OSO-7* and at the Earth where the effects were magnetic storm sudden commencements. He assumes that the interplanetary waves decelerated linearly, in which case the calculated initial velocities at the Sun are not inconsistent with those of the Type II bursts: this could explain Hartz's result, and at the same time it complicates the interpretation of spacecraft data since we may not be able to assume constant velocities

along the Sun–Earth path for storm particles. Deceleration of interplanetary shock waves as they expand and propagate through the solar wind plasma (Sect. 9) was discussed earlier by Wilcox.[141]

Thus we are not able to say with certainty when a magnetic storm will begin except to say that, other things being equal, the more intense events will produce disturbances in little more than a day and the least (which will produce disturbances at all) in about 3 days. Similarly, the more intense and long-lasting solar events tend to produce the more severe storms, but it should be noted[142] that 'the magnetic field (i.e. relating to storm intensity) and velocity of ejection of a plasma blob from a flare region are independent quantities' so it is quite possible to have a severe storm with long delay time and vice versa.

## 6 The Line-emission Corona and Magnetic Disturbances

In Sect. 2.2 we mentioned the significance of coronal line emission in identifying active solar regions. Early superposed-epoch studies of enhanced corona and magnetic disturbance produced conflicting results because they covered limited periods of time at different parts of the solar cycle. As reviewed by Bell and Glazer[143] and Warwick,[144] it became clear that at low sunspot number, c.m.p. of relatively enhanced corona is followed by a minimum in magnetic activity, while at high sunspot number enhanced coronal regions are to be identified with active centres which are themselves producers of magnetic storm particles, and we observe a magnetic activity maximum after c.m.p. As will be seen in Sect. 7, the solar regions associated with recurrent storms near sunspot minimum tend to avoid the active centres. A study by Denisse and Simon[145] of magnetic activity curves around (a) 40 centres of activity with yellow line emission and (b) 23 without, found an increase around c.m.p. of (a) while there was a slight decrease for (b), a result very similar to that already found for the R and Q spots (Sect. 5.5, ref. 112).

The green line emission has been examined again recently by Gulbransen[146] in relation to the solar wind structure (see Sect. 9) and recurrent magnetic storms (Sect. 7), for the years 1958–64, i.e. the declining branch of solar cycle 19. Zones of low coronal intensity extending both north and south of the solar equator (called L zones) are found to be followed by onset of magnetic disturbance about 2 days after c.m.p., these disturbances being the recurrent storms which are a feature of the years approaching sunspot minimum.

## 7 Recurrent Storms and M-regions

The existence of two kinds of magnetic storms, one typically strong, with sudden commencement, sporadic, related to sunspots and sunspot activity, and the other weaker, with gradual commencement, long-lasting and not related to sunspot but tending to recur at 27-day intervals, was mentioned in Sect. 5.1. A third group not recurrent but not related to specific events either, will be discussed in Sect. 8.

Bartels[147] arranged the magnetic disturbance indices for the years 1906–31 in rows of 27 days (one solar rotation) so that dates 27 days apart appear in vertical columns (the well-known Bartels diagram) and compared them with other solar phenomena, from which 'we infer the existence of certain restricted areas of the Sun's surface which are responsible for terrestrial-magnetic disturbances, and which we propose to call M-regions. They appear to be more long-lived than sunspots. The identification of M-regions with sunspots or other solar phenomena is possible in some cases only, while in many cases the M-regions lead, so to say, an independent life.' Shapley,[148] investigating the recurrence-tendency for forecasting purposes found, for 2 years after sunspot maximum to and including the sunspot minimum year, a strong 27-day recurrence with lesser maxima at 54 and 81 days. There were also high values for 1, 2 and 3 days showing that the 'time unit' for magnetic storms is about 3 days, but this analysis included the strong s.c. non-recurrent storms which accounted for most of the activity. Many others have confirmed this pattern, notably E. and O. Thellier[149,150] in a study of 688 magnetic storms between 1884 and 1947, and the picture which emerges is that of a class of geomagnetic disturbances with the following characteristics:

(1) moderate to weak intensity, but long duration, up to 10 days or so;

(2) gradual commencements usually;

(3) 27-day recurrence tendency over a long period, up to a year, with maximum disturbance around the equinoxes;

(4) more noticeable in the years approaching sunspot minimum;

(5) negative correlation with sunspots, but the recurrence period decreases by about half a day from sunspot maximum to minimum, as though the emitting zones migrate towards the equator during the cycle, as do the sunspot zones.

Since these storms are of long duration, and occur when the ionosphere critical frequencies are decreasing along with the sunspot number, their effect on radio communication is relatively great [151] and it would be useful to relate them to observable solar features. Many were suggested, e.g. areas vacated by sunspots,[152] areas of diminished coronal line emission,[153] and large areas of the Sun's surface having the same magnetic polarity (unipolar magnetic regions),[154,155] and a study which has stood the test of time was made by Allen[114] in 1943. He divided the magnetic disturbances 1906–42 into four groups on the basis of their recurrence; those which began a recurrent series (B), or ended one (E), or occurred within a sequence (M) or had quiet periods 27 days before and after (T). Thus the T storms are those we have called sporadic while the M storms might signify the existence of a fairly stable M-region. The study confirmed the relation between major flares and great storms while showing no connection between lesser flares and weaker T storms (as would be expected from a study based on the optical flare data only without reference to the radio events), but showed also that

M-regions tend to avoid the areas within about 40° of sunspot groups and to be more frequent than normal just outside this area. Allen suggested that the M-region 'is more likely to be an emission coming from practically the whole of the Sun's surface and constrained to move in streams by forces in the Sun's atmosphere. It would then be the continuity of these streams that cause the persistence and changes of the recurrent magnetic storms'. These ideas were taken up later by Pecker and Roberts[156] who coined the phrase 'cone-of-avoidance' for the deflexion of M-streams away from centres of activity on the Sun in agreement with the forms assumed by coronal streamers in eclipse pictures, and again by Saemundsson[157] who while agreeing with the cone-of-avoidance idea maintained that M-regions are largely independent of active areas.

A different interpretation of the recurrence statistics has been given in a long series of papers by Mustel' and co-workers (see e.g. refs. 158–160) who related all geomagnetic disturbances to the passage of bright calcium regions (flocculi) near the centre of the Sun's disk, these flocculi producing radial streams of particles with velocity dispersion which could explain the long duration of some recurrent storms. The c.m.p. of these regions is followed by a minimum in disturbance after 3 days and a maximum around 3 days after that (which might be taken as support for the cone-of-avoidance idea) but according to Saemundsson,[157] Mustel's explanation that the 3-day minimum is an effect of the distribution of flocculi in longitude is not correct because the flocculi are not arranged in this way, and if the 6-day maximum were due to c.m.p. of all centrally-located flocculi the maximum should be much greater than it is observed to be. Spacecraft measurements of the actual particle velocities might help to resolve this problem, and in the next 2 years Snyder *et al.*[161] presented data on the observed plasma velocities at *Mariner II* which was in such a position that time lags greater than 1 day would not be expected between the spacecraft and the Earth. They found velocities varying between about 300 and 600 km/s (equivalent to 3–6 days radial travel time from the Sun to Earth), correlating strongly ($R = 0{\cdot}73$) with the daily magnetic disturbance index. Their diagrams show that for days when the daily $Kp$ sum exceeded 20 (which roughly distinguishes days of M-disturbance from other days of only slight disturbance), the plasma velocity exceeded 500 km/s (around 3 days travel time).

Useful reviews of the M-region arguments at this stage were given by Allen[162] and Obayashi[163] and later by Mustel'[164] who now divides recurrent disturbances into R-type associated with the 'optical-magnetic' stage of development of active regions, that is with the calcium plages and local magnetic fields, in the ascending as well as the descending part of the solar cycle, and M-type or the classical recurrent storms of the descending part of the cycle. The plasma velocity measurements of Snyder *et al.*[161] were made at distances at least 0·7 of the Sun–Earth distance. Brandt[165] points out that although the velocity may be 600 km/s at 1 A.U. (the Earth's distance from the Sun) it may be only 16 km/s at 0·1 A.U. if the equation of continuity applies, because of the decrease in density as we move out from the Sun, so we may have appreciable delays up to a month or so for particles starting from the lower chromosphere. This would remove some of the objections to Mustel's arguments.

Three more recent lines of research now lead to possible identification of M-regions with observable features. A study by Roosen[166] of 9·1 cm radioheliograms during 1964 (sunspot minimum period with well-marked recurrent disturbances), allowing for brightness variation with distance from solar disk centre and with some limiting assumptions about the expansion of the coronal gases, relates the c.m.p. of areas of brightness depression with enhanced geomagnetic activity about 4 days later. These depressed brightness areas are found to persist for many rotations and to outlive any optical features which might have been related to the disturbances early in the sequence.

Secondly, in Sect. 6 we mentioned Gulbransen's[146] L zones, which partly coincide with Roosen's areas of diminished 9·1 cm brightness. These L zones will be discussed again in Sect. 9. Finally, there are the recent observations of 'coronal holes' (see e.g. Altschuler *et al.*[167]) which are regions of very low coronal density above quiet chromosphere, and above which the magnetic field lines in the corona are weak and diverging. According to Krieger *et al.*[168] such a hole observed in an X-ray picture of the Sun on 24th November 1970 is identified as the source of a high velocity solar wind stream on three successive solar rotations. The recurrent disturbances following c.m.p. of this region on 29th September and 26th October were slight, however, and a third recurrence was masked by a sudden-commencement storm already in progress.

We will return to these developments in Sect. 9. Meanwhile the established 27-day recurrence patterns, the development of active regions which might disrupt this pattern, and detection of solar wind sector boundaries (Sect. 9) remain the main forecasting tools during solar-quiet periods at this stage (1974) of the current solar cycle.

## 8 Sporadic Storms Not Related to Flares

The magnetic storm-flare (optical and radio) relationships outlined in Sect. 5 account for the severe storms (with a few notable exceptions mentioned in Sect. 5.6), and for many of the moderate storms, while the well-defined recurrent sequences have been discussed in Sect. 7. There remains, however, a number of moderate to weak storms, including Dodson and Hedeman's 'problems',[130] which do not fit in with either of these patterns.

From the superposed-epoch studies listed here, it is tempting to assume that the remaining disturbances are the result of many small events none of which can be singled out as a primary source of storm particles. Alternately, are they the effect of some (temporary) property of regions crossing the solar disk, akin to the long-lived property of the hypothetical M-regions?

One of the effects of a magnetic storm is a decrease in cosmic ray flux (Forbush decrease)[169] caused by the

immersion of the Earth in the stream of charged storm-particles. Ballif *et al.*[170] related these to the c.m.p. of flare-producing regions rather than to the flares themselves. There was a broad maximum in class 2 or greater flares just before the decreases (and magnetic storms) occurred. Much earlier, Barsukov[171] in a study of 233 flares in eight longitudinal zones on the Sun's disk found a broad maximum disturbance centred on c.m.p. plus 3 days of regions 'where flare has occurred, or will occur'. But the flare-storm relationships discussed in earlier Sections lead to similar results, since the flares occur in sunspot regions, so there is no real conflict with the flare-storm evidence from Newton[88] on.

Bednářová-Nováková and co-workers, in another long series of papers (see e.g. refs. 172, 173, 41, 174–176) relate magnetic storms to the passage of filaments (prominences when seen in H-alpha at the Sun's limb) across the centre of the Sun's disk. These filaments may be in active sunspot groups, or isolated, and when seen on the limb are associated with corresponding formations in the optical corona. In ref. 175 formations described as helmets, streams and 'wings' of the sunspot-minimum corona are sketched from records of 33 solar eclipses 1893 to 1966 and related to geomagnetic activity at c.m.p. of the east and west limb features, with success claimed in 27 of the 33 cases, but in many cases it is necessary to invoke 'possibility of changes' and to remember that what we see in projection against the dark sky is a large slice of the corona. In this paper, the authors repeat the suggestion that a spacecraft in solar orbit 90° away from the Earth might usefully record the coronal formations directly opposite the Earth.

In ref. 173, the coronal formations and disk filaments are related in this way:

(1) 'Bound' filaments associated with strong magnetic fields show a split corona with streams directed away from the radial direction leaving a 'cone of emptiness', and magnetic quiet at c.m.p. These correspond to quiet sunspots and the 'cone of avoidance' discussed earlier, which produce quiet conditions.

(2) 'Bound' filaments associated with weak fields appear in plages without spots, and show a helmet coronal formation, with magnetic quiet at c.m.p., as would be expected from the lack of activity in these regions.

(3) 'Unstable' filaments associated with varying magnetic fields in active regions show streams, more or less radial, and occasional eruptive prominences, with magnetic disturbance after c.m.p. These correspond to the active sunspots which produce flare events, and disturbances.

(4) 'Free' filaments which form where sunspots have disappeared, and there are no disturbing magnetic fields, show 'wings' of minimum-type corona, and weak disturbances after c.m.p. These might correspond with unipolar magnetic regions (Sect. 7, refs. 154, 155) and recurrent disturbances.

Thus the two schools of thought can be reconciled, but disagreement remains on the association of *all* disturbances with c.m.p. of filaments and streams by the Czech group and their rejection of the flare-storm association. This is difficult to accept in view of the radio evidence for ejection of particles from flares, e.g. by Stewart and Sheridan[101] who related the Type II and Type IV bursts at 0130 UT on 21st March 1969 to a common disturbance presumed to be the advancing shock front from the flare, and for which the moving Type IV was tracked on the Culgoora heliograph. A magnetic storm was forecast on the basis of this event and occurred 65 hr later. Pintér's work[140] on Type II and storm particle velocities also points directly to the flares as the particle sources, in these cases.

To look further into the problem of the disturbances which cannot be related to obvious events, including those which appear to be recurrent, we need to consider the solar wind and its sector structure.

## 9 Magnetic Storms and the Solar Wind Structure

Expansion of the coronal plasma into interplanetary space was given the name 'solar wind' by Parker (see e.g. ref. 177) who pointed out that since the radially expanding plasma carries magnetic field with it from the Sun, the magnetic field pattern should assume a spiral form because of the Sun's rotation. This pattern would then rotate with the Sun, overtaking the Earth (or a spacecraft) every 27 days or so. From observations with the spacecraft *IMP-1* in 1963, Wilcox and Ness[178] found a 4-sector structure in which the interplanetary magnetic field was directed alternately towards and away from the Sun, and in which 'a recurring stream of protons of a few MeV energy is almost entirely contained within one sector'. This was at sunspot minimum. At sunspot maximum (1968–69) there were two sectors[179,180] and we will see later how this relates to other ideas on how the Sun's activity is organized.

A comprehensive review of the work up to 1967 is given by Wilcox.[181] We will discuss here only a few aspects of this subject, much of it published since 1967, which lead to the possibility of forecasting geomagnetic effects from observations of sector structures.

### 9.1 Sectors and Solar Streams

The idea of streams in the solar wind is not new and was the theme of Sects. 7 and 8, but we need to consider what happens at the boundaries between streams of different velocities as emphasized by e.g. Piddington,[182] and Hirshberg.[183] Mustel', in his review of M-regions,[164] spoke of tongues of faster gases pushing through the slower solar wind, and Wilcox[184] discusses the existence of subsectors within the 'toward' or 'away' sectors in which the interplanetary field (and other parameters) vary in strength and direction but not enough to change the sign of the field.

### 9.2 Magnetic Disturbance and Sector Parameters

An early observation by Snyder *et al.*[161] that the magnetic disturbance index *Kp* correlates well with solar plasma velocity was mentioned in Sect. 7. Wilcox *et al.*[185] related *Kp* to both velocity and interplanetary

magnetic field magnitude during quiet-sun conditions while Ballif *et al.*[186,187] find that *Kp* correlates better with fluctuations (measured by variance over 3-h intervals) in components of the interplanetary field than with either the field intensity or plasma speed. From Parker's Archimedean spiral picture[177] a sudden increase in plasma velocity would tend to straighten out the spirals thus causing a change in the average field direction. 'Away' sectors also appear to be more effective geomagnetically that 'toward' sectors.[188,189]

It was suggested some twelve years ago by Dungey[190] that if the interplanetary magnetic field, at the Earth, were directed southwards, solar plasma would penetrate the Earth's magnetic field more easily. Spacecraft measurements already referred to, by Schatten and Wilcox[185,189] and by Fairfield and Cahill[191] (*Explorer 12*), Rostoker and Fälthammar[192] (*IMP-1*), Arnoldy,[193] and Bobrov[194] appear to support this idea although Hirshberg and Colburn[195] state that the relationship between *Kp* and the magnitude of the interplanetary field is independent of its direction (north or south). Oguti[196] indeed identifies 17 kinds of magnetic storm depending on whether the 'solar bubble' occurs in an 'away' or 'toward' sector, with the interplanetary field directed north or south, and whether the bubble is or is not preceded by a shock wave, and gives examples of magnetic records of each kind. Some of the problems in relating measurements made by different spacecraft at different levels of geomagnetic activity are discussed by Mansurov and Mansurova.[197]

Finally, Wilcox and Colburn,[180] in their discussion of sectors near solar maximum, confirm a result found in earlier work at sunspot minimum[178] and on the rising part of the solar cycle that geomagnetic activity is less when the Earth is in the trailing part of a sector (i.e. just before a sector boundary sweeps past the Earth) than in the leading part (i.e. just after a sector boundary passage).

### 9.3 Sector Structure in Solar Activity

In Sect. 2.2 on evolution of active regions the apparent concentration of solar activity in certain preferred longitudes was mentioned.[26–28] This is now seen to be related to the four-sector structure of the solar wind observed at sunspot minimum and the two sectors at sunspot maximum. Another way of looking at it is to say that we have stable quiet areas with activity concentrated at the boundaries between them so that Earth-passage of a boundary in the associated solar wind structure is followed by geomagnetic effects of the activity. For forecasting purposes then we need to identify these areas and boundaries on the Sun or in space as they approach the Earth.

On the radio Sun, Roosen's[166] centimetre-wave 'coronal depressions' were discussed at the end of Sect. 7. At metre wavelengths (169 and 408 MHz) Sakurai and Stone[198] relate source regions of Type I emission (see Sect. 5.4, ref. 103) to the sector boundaries; at these wavelengths the sources are located in the outer corona where the coronal streams are observed optically, and it is suggested that the configuration of the photospheric (solar surface) magnetic fields extending into interplanetary space is related to these Type I radio regions. Optically, Gulbransen's L zones[146] in coronal line emission, lying east of the sector boundaries, were also discussed in Sect. 6. Sawyer and Hansen[199] find correlation between equatorial arches in the white-light corona and the sector boundaries themselves, with slight increase in geomagnetic disturbance about 5 days after c.m.p., in agreement with Sakurai and Stone's radio source regions.

The identification of a solar sector with a large area of weak photospheric field extending either side of the solar equator had been made earlier by Wilcox *et al.*,[200] with subsectors[184] associated with increased activity east of the boundary (i.e. on the following side, so that activity directed towards the Earth follows c.m.p. of the boundary). This appears to account also for the geomagnetic storm 'families', i.e. disturbances separate but associated in some way, discussed in a long series of papers by Afanas'yeva.[201] The coronal arches have also been discussed in more detail by Wilcox and Svalgaard[202] who found that the sector boundaries extended almost to the north and south poles of the Sun, and did not undergo differential rotation as do the surface features at different solar latitudes.

### 9.4 Detection of Sector Boundaries: the Svalgaard-Mansurov Effect

Since an abrupt change in the polarity of sector magnetic field signifies the arrival of a sector boundary at the point of measurement, it would be useful to have some Earth-based method of detecting such an event. Svalgaard[203,204] and Mansurov[205] have discovered such a method, based on geomagnetic field behaviour at observatories within about 8° of the geomagnetic poles (e.g. Thule, Resolute Bay, in the north, Vostok in the south). When the Earth is immersed in an 'away' sector (positive polarity by definition), the vertical component $Z$ of the Earth's field at Thule or Resolute Bay is decreased for several hours near noon, and increased at Vostok, while the effect is reversed for 'toward' sectors (negative polarity). A little further away from the geomagnetic poles, e.g. at Godhavn, the horizontal component H is found to increase on 'away' days and decrease during 'toward' days. In the Earth's magnetospheric tail, the lines of force are directed away from the Sun above the south polar regions and towards the Sun in the northern, so that a change in the sign of the interplanetary field component parallel to the Sun–Earth plane would be expected to produce the effect shown.

The effect is discussed further by Friis-Christensen *et al.*,[206] by Wilcox,[207] who mentions its application in current short-term forecast services, and by Svalgaard[208] whose 1973 review[209] is the latest available on this promising method of detecting sectors. It is agreed by these authors that there are ambiguities and some days when apparently wrong answers are given. Campbell and Matsushita[210] in a test of the technique for 1965 published at the same time as ref. 209, using automated methods rather than visual in estimating the quiet-day magnetic curves for Thule, Resolute Bay and Godhavn

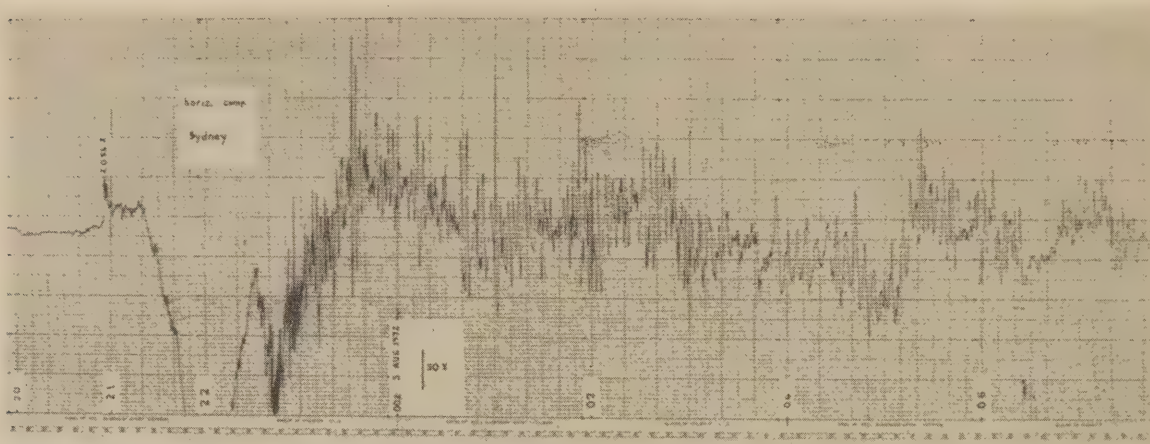

**Fig. 8.** The great magnetic storm beginning 4th August 1972, showing sudden commencement at 2056 UT. Horizontal component of Earth's field recorded at Sydney.

(from which the variations are measured), found agreement between the appropriate values of $Z$ and sector field on only 61% of the days. This rose to 70% for the summer period only.

Thus it is clear that this method, like many other solar-terrestrial relationships mentioned here, must be used with caution. Many of the measured disturbances, particularly around sunspot minimum, are small and not significant from a communications point of view, and even for the major storms we have shown that there will still be failures to forecast, and false alarms occasionally.

Now before outlining current forecasting services and data exchange arrangements, we will mention briefly the ionospheric disturbances which accompany the geomagnetic storms and other solar effects and which represent one of the main reasons for attempting to forecast the storms.

## 10 Ionospheric Effects of Magnetic Disturbance

While much effort has been expended in the past in attempting to forecast solar activity and magnetic storms for various purposes (including assistance to radio communicators), the effect on the ionosphere of a magnetic storm, once it has begun, has also proved difficult to predict in detail. A magnetic storm is a global affair, but as mentioned in the Introduction to this paper we are concerned with the ionosphere at a specified point at a specified future time. Much depends, of course, on the nature of the magnetic storm (Fig. 8). Here we will touch on just a few of the attacks on this problem, considering mainly the F-region. D-region fadeouts were discussed in Sect. 3 and polar cap absorption in Sect. 4, and will not be considered further here.

### 10.1 Morphology of Ionospheric Disturbance

One of the earliest mentions of the ionospheric effect of magnetic disturbance appears to have been made by Appleton and Ingram[211] in 1935. Comparing Slough midnight foF2 values and the Abinger magnetic character figures for the preceding 24 hours, they found *f*oF2 decreased during magnetic disturbance. The noon values' behaviour was 'not quite as simple'. Kirby *et al.*[212] examined noon values during the severe storm of 23rd–24th October 1935 and found *f*oF2 decreased (having been high 16th–23rd October) and $h'$ increased, and suggested that heating may have produced expansion of the F-region leading to increased virtual height and decreased critical frequency. Martyn[2] resolved the *f*oF2 departure from normal into (magnetic) storm-time Dst and daily variations D.S. in the same way that magnetic storms had been analysed and found a distinct dependence of the morphology on local time of commencement of the magnetic storm.

The first of several comprehensive reviews of the subject was made by Matsushita[213] in 1959 and from this the general picture emerged. The Dst variation at higher latitudes comprised a short increase in *f*oF2 followed by a much larger decrease (greater in summer), with variations of opposite phase in equatorial latitudes (Fig. 9). At intermediate latitudes, the phase changed with the seasons, resembling higher latitudes in summer and equatorial in winter. The D.S. variations decreased from higher toward lower latitudes with subsequent equatorial increase, the phase changing also with geomagnetic latitude. Matsushita presented also a table (Table 5 in the paper) showing the most probable hour for a large decrease in *f*oF2 in local time and storm time reckoned from the magnetic s.c.

An analysis of *f*oF2 disturbances at middle latitudes, reckoning from onset of the main phase of severe storms instead of the s.c., was made by Thomas and Venables,[214] showing that when this occurs at night, *f*oF2 is immediately depressed, while if it occurs during the day there is either an increase or no change, followed by decrease in the evening. High latitude investigations were made by several workers, e.g. Zevakina[215], but were complicated by polar cap absorption and auroral ionization. Duncan[216] discussed the so-called 'winter anomaly', that

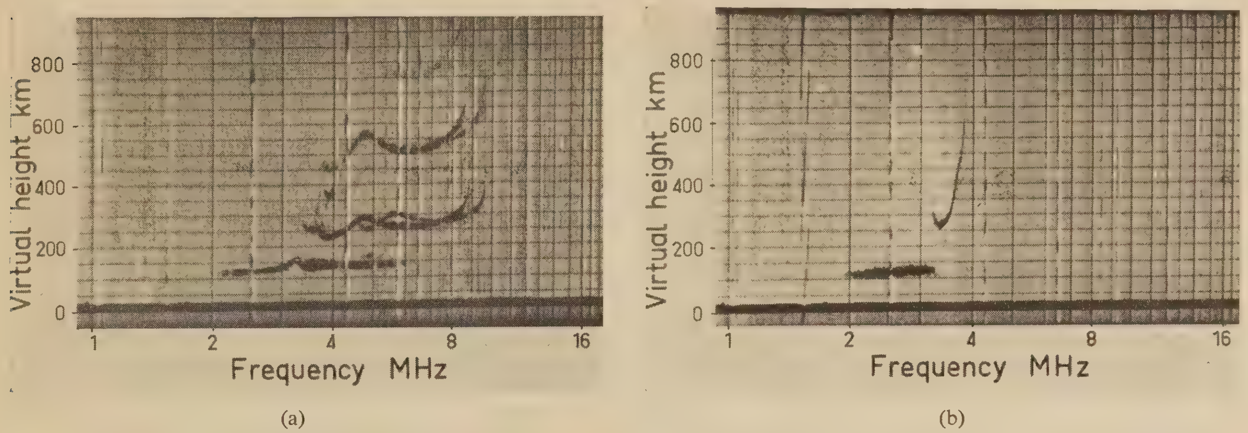


**Fig. 9.** Canberra ionogram associated with magnetic storm.
(a) Near local noon (0200 UT) on 4th August 1972 showing quiet ionosphere before the magnetic storm.
(b) Near local noon one day later, on 5th August, during severe magnetic storm.

winter daytime *f*oF2 was found to be greater than summer daytime *f*oF2, and extended his explanation to ionospheric-magnetic storm behaviour. In summer, magnetic storm heating of an already heated ionosphere reduces *f*oF2 and increases *h'*, while in winter magnetic disturbance prevents the settling (at low latitudes) of air rich in atomic oxygen which would otherwise collect electrons and reduce the electron density, hence *f*oF2 there remains high.

### 10.2 Ionospheric Disturbance and Magnetic Storm Characteristics

Accounts of the currents in the magnetosphere and ionosphere, and their effects which we measure directly as magnetic storms or observe as ionospheric storms, are given in many textbooks, e.g. by Piddington[217] (Chapters 8 and 9). These suggest that foF2 behaviour during storms might relate to variations in the magnetosphere ring current. Zevakina *et al.*[218] found Dst ($\Delta f$oF2), i.e. *f*oF2 departures from quiet-day medians, to vary with Dst (H), the storm-time variation of the horizontal component of the Earth's field, but Mendillo[219] found Dst (H) unsatisfactory and relates the total ionospheric electron content measurement to variations in the local measurements of the total magnetic field (F). An enhancement is found in the afternoon period following a magnetic s.c. unless there is an intervening post-midnight period with strong depression of the magnetic field. Similarly Cole and McNamara[220] found *f*oF2 variations to depend on local time, latitude and magnetic storm onset times: following a magnetic storm onset at night, *f*oF2 depression is most likely between 1800–1200 local time, while increases avoid the period 0400–1200 h. A review of work up to 1969 is given in Akasofu and Chapman[6] (Chapter 8.10).

These studies enable the forecasting services to give their users more information than the simple fact that a magnetic storm (forecast or not) has begun, but the erratic nature of *f*oF2 'at a specified point' should be kept in mind. Kane[221] for example in a more recent study says that deviations from the average pattern (decreases at mid-latitudes and increases at near-equatorial latitudes) 'seems to be more a rule than an exception'.

## 11 Operational Warning Services

The solar-terrestrial relationships described here (and others, particularly in the magnetic storm-ionospheric effect area for which there is no more space in this paper) are basic to short-term forecasting. The ways in which these relationships are assessed and applied varies between the different forecasting groups, and since the emphasis is continually shifting from one area to another as understanding increases, and with users' requirements, it is not surprising that there are few published 'how to do it' manuals on the forecasting of disturbances, from all causes, within actual operating systems. Earlier systems were mentioned at the beginning of this paper (refs. 9–13, 18, 19) and aspects of some current ones are described in refs. 17, 20, and by Salaman[222] and Ochs.[223] Others are contained in working papers kept at the Warning Centres, or in 'house' journals by, e.g., Marconi Radio Propagation Services (D. G. Cole, private communication). Evaluation of these systems and methods comes within the terms of reference of the International Radio Consultative Committee (CCIR) Study Programme 10A/6 on 'Identification of precursors indicative of short-term variations of ionospheric propagation conditions', and is also the concern of the Special Committee on Solar Terrestrial Physics (SCOSTEP) of the International Council of Scientific Unions (ICSU).

Basic to all these considerations is the necessity to observe and record the solar activity and its effects 24 hours a day, and to exchange the data so obtained rapidly between Warning Centres in the different longitudes. This is the province of the International Ursigram and World Days Service[21] which is a Permanent Service of the International Union of Radio Science (URSI) in association with the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (IUGG), having Regional Warning Centres

at Boulder, U.S.A., Paris, Darmstadt, Moscow, Tokyo and Sydney, and Associate Centres at Stockholm, Prague, Irkutsk and New Delhi, and designated Warning Contacts in member countries. These Centres organize the collection of data from Observatories in their Regions, and from their own observations, and exchange these data, warnings, and 'advices' of various kinds several times a day with other Regions. Some organizations based in the U.S.A. have independent rapid data observation and exchange systems but solar data from these sources are fed into the IUWDS system also. Ref. 21 describes the IUWDS operations in detail.

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*Manuscript received by the Institution on 23rd May 1974. (Paper No. 1620/Com. 101.)*

UDC 621.319.812.63 + 621.391.812.8

# Long-term h.f. propagation predictions for radio-circuit planning

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SUMMARY

When an h.f. radio circuit is being planned, the specification of the transmitter frequency range and radiated power and the choice of transmitting and receiving aerials are determined from propagation considerations. The factors involved in prediction techniques for the case of ionospheric signals are outlined. Current procedures used internationally and their proposed future improvements are described.

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## 1 Introduction

High-frequency radio waves propagating via the ionosphere are used for a variety of purposes including, in particular, fixed and mobile point-to-point communication and broadcasting. At h.f. several tens of thousands of circuits with bandwidths of a few kilohertz are operated simultaneously so that many of these are co-channel, relying on geographical separation to avoid mutual interference. Circuit planners need to know what frequency ranges their systems should be capable of covering, what transmitter powers are necessary to overcome the background noise at the receiver and what aerial configurations will best beam the signals to the required receiving terminal or terminals. These are all factors dictated by propagation considerations. Whilst rule-of-thumb assessments based on past experience can sometimes be made, the capital outlay involved in setting up a system in most cases makes recourse to the best-available prediction procedures well-worthwhile. Moreover, internationally-agreed prediction methods are needed as an adjunct to frequency-assignment schemes which involve estimating the possible effects on existing radio circuits of each proposed new transmitter.

Since the early days of radio considerable effort has been expended in a number of countries on the development and testing of field-strength prediction methods. Some of these methods use theoretical relationships based on estimates of the prevailing state of the ionosphere[1–5]; others involve empirical equations fitted to trends in measured field-strength data.[6] Empirical prediction methods usually have the advantages of simplicity but are produced from limited data which may not be representative of the full range of conditions for which they may be required to apply. Many of the causes of variability of these data cannot be isolated and have to be regarded as unknown, so that prediction uncertainties are relatively high. By contrast, analytical methods include detailed allowances of some propagation factors, but other equally important factors tend to be ignored, either because of their numerical complexity or because the physical processes involved are incompletely understood.

There is now a general realization that at m.f., because of the extreme variability and current unpredictability of the lower ionosphere, empirical field-strength prediction methods are preferable.[7] At h.f. by contrast, signals are influenced mainly by the ionization in the E and F regions of the ionosphere and, since the morphology of this is known with greater precision than that of the D region, it seems probable that analytical prediction methods will be the more accurate. Even so, h.f. field-strength prediction methods in the past have generally been poor, with long-term median signal intensities sometimes differing from those predicted by up to 20 dB. In such circumstances it is understandable that prediction procedures have been treated with scepticism and that circuit planners advocate the use of greater transmitter powers than necessary. However, as spectrum pollution becomes an ever more severe problem the need for accurate predictions is increasing and will continue to do so.

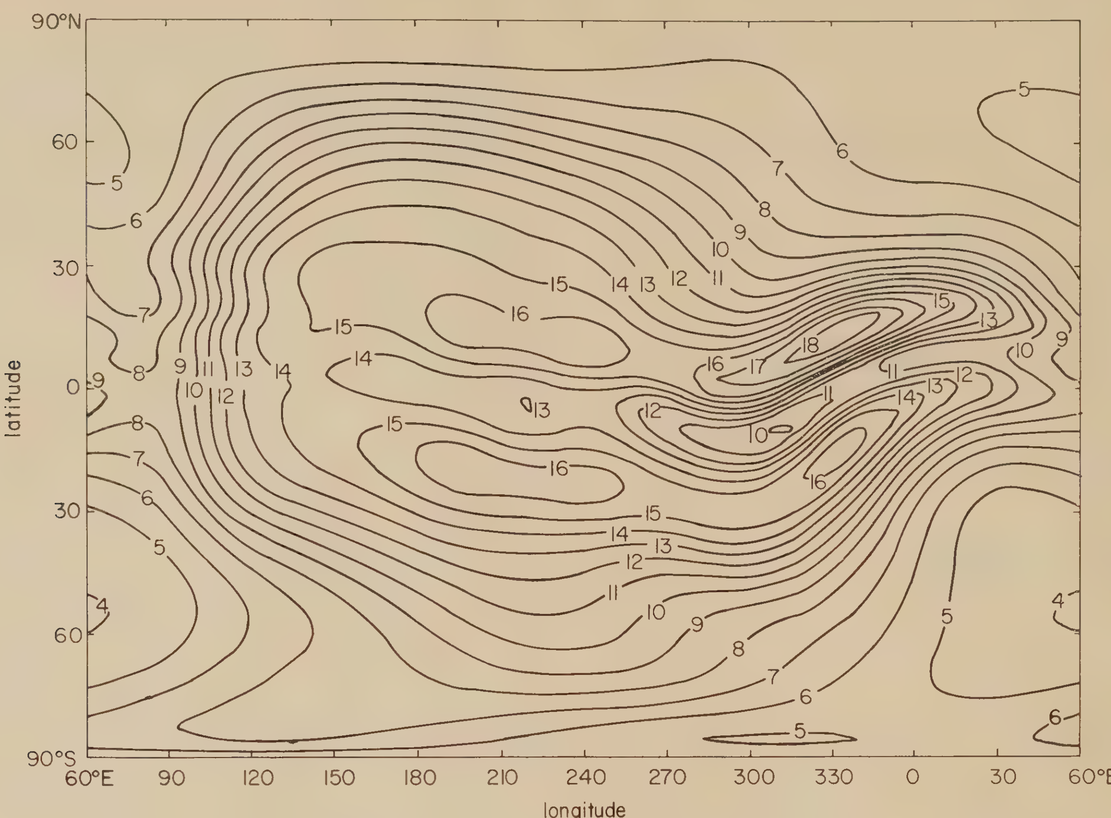


**Fig. 1.** Predicted median $f$oF2, MHz for 00 hours UT in March 1958.

It is fortunate that recently improved knowledge of ionospheric morphology, coupled with the greater availability of high-speed and large-storage digital computers, now makes possible the development of more accurate prediction methods. This paper describes the method currently advocated for use by the International Radio Consultative Committee (CCIR),[8] and discusses the modifications which it has been agreed will shortly be introduced.[9] Section 2 considers the representation of the ionospheric conditions and Section 3 shows how the raypaths of the active propagation modes are determined. The transmission-loss factors influencing received signal intensity are examined in Section 4. Section 5 discusses the background noise against which the wanted signals must compete and in Section 6 the application of the prediction data to the choice of circuit design parameters is outlined.

## 2 Ionospheric Conditions

The starting point for any modern analytical prediction method must be a representation of the vertical distribution of electron concentration in the E and F regions of the ionosphere up to the height of maximum electron concentration, since this distribution determines the signal raypaths. Accurate prediction methods must take account of the known large geographical and temporal variations of this distribution. The most extensive ionospheric data base is that derived from the world network of vertical-incidence ionospheric sounders (ionosondes). Hence in both the existing CCIR prediction method and its proposed improvement, models of the vertical distributions are produced with the parameters of the models given by empirical equations in terms of the ionospheric characteristics which are scaled on a routine basis at all ionosonde stations.

The standard ionospheric characteristics include $f$oF2, which is the maximum plasma frequency of the F2 layer; $f$oE, the maximum plasma frequency of the E layer; $f$oEs the maximum sounding frequency at which detectable echoes are received from the sporadic-E layer; $M$(3000)F2 the maximum usable frequency factor for propagation via the F2 layer to a ground range of 3000 km; $h'$F2, the minimum observed virtual height of reflexion of signals from the F2 layer and $h'$F, the minimum observed virtual height of reflexion of signals from the F region as a whole. All of these characteristics are measured each hour at over 100 stations and from analyses of past data long-term median trends have been established so that future values can be forecast.

A convenient representation of each characteristic (referred to below as $\Omega$) as a function of geographic latitude $\lambda$ longitude $\theta$ and Universal Time $T$ for a given month and level of solar activity has been devised by Jones *et al.*[10,11] This is based on orthogonal polynomial expressions, with $\Omega$ given by the time series:

$$\Omega(\lambda, \theta, T) = \Sigma_j[a_j(\lambda, \theta) \cos jT + b_j(\lambda, \theta) \sin jT]$$

The $a$ and $b$ give the latitude and longitude variations,

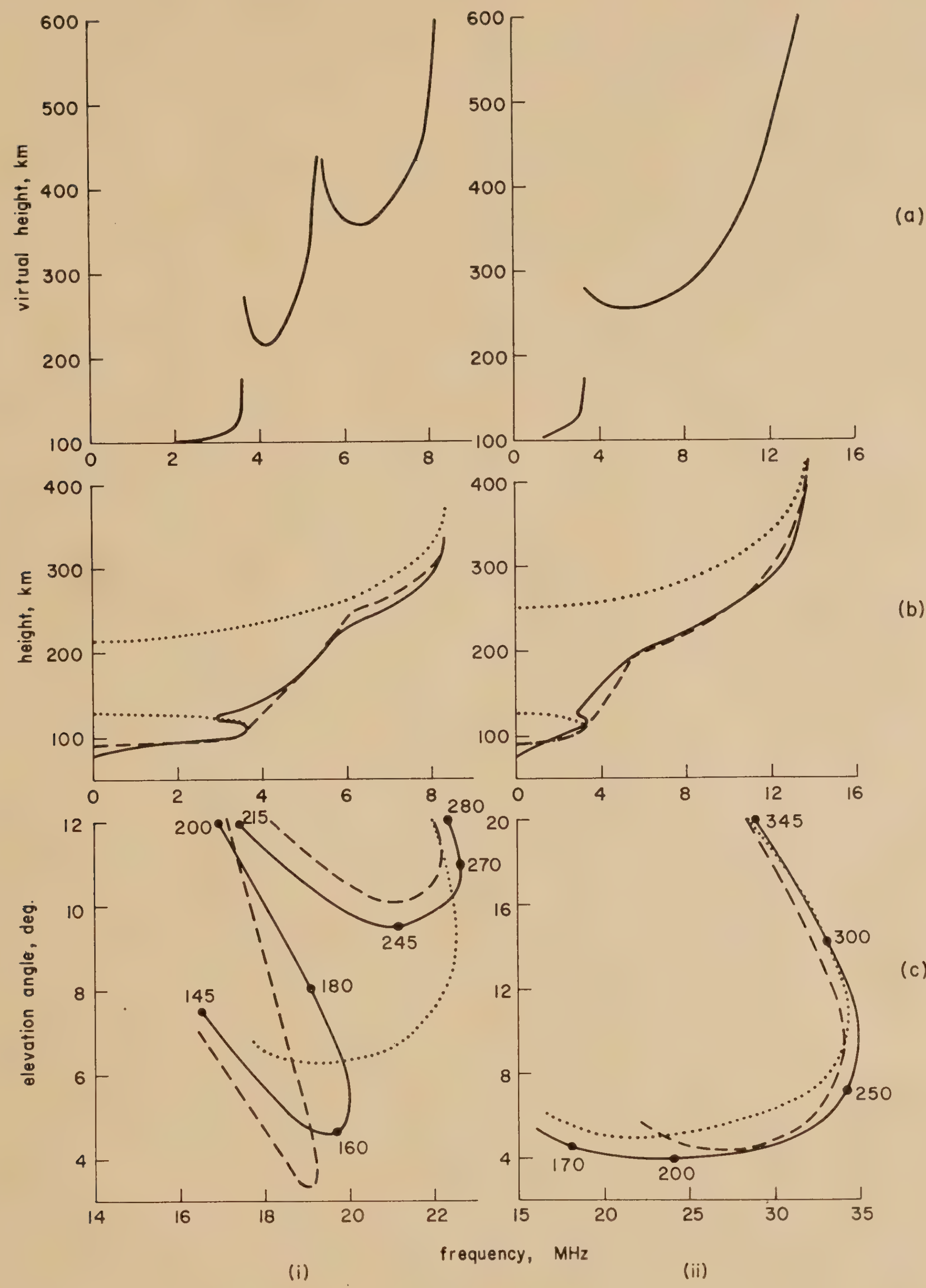


**Fig. 2.** Accuracy of electron-concentration distributions and corresponding mode plots obtained using existing CCIR model and proposed new model.

Column (i): ionogram showing F1 cusp    Column (ii): ionogram with no F1 cusp present

(a) recorded ionograms
(b) vertical distributions of electron concentration
(c) mode plots for propagation to a range of 3000 km

—— from true-height analysis    ---- from new model    .... from existing CCIR model

Numbers quoted on diagram are ray apogees in kilometres.

being defined as

$$a_j(\lambda, \theta) = \Sigma_k U_{2j,k} . G_k(\lambda, \theta)$$

$$b_j(\lambda, \theta) = \Sigma_k U_{2j-1,k} . G_k(\lambda, \theta)$$

The $U$ are numerical coefficients and the $G$ are trigonometric functions of latitude, longitude and modified dip latitude. The number of terms in the summation varies for the different characteristics depending on the amount of variation to be mapped. A separate numerical representation has been produced for each month and for reference high and low levels of solar activity. Linear interpolation in terms of smoothed sunspot number is assumed to apply. Figure 1 gives an example of a prediction map for $f$oF2 based on 988 numerical coefficients $U$.

Models of the electron concentrations with parabolic vertical distributions are popular both because they are a fairly good approximation to measured data and because radio-wave propagation at oblique incidence via such models has been extensively studied.[12] The existing CCIR model is shown in Fig. 2(b). It consists of a parabolic F layer with height of maximum electron concentration given in terms of $M$(3000)F2, and base height given in terms of $h'$F. The E layer is parabolic with fixed height of maximum electron concentration and semi-thickness of 110 and 20 km respectively. The model which will be introduced in the new CCIR prediction method[13,14] also has parabolic E and F2 layers, but the F1 ionization is represented as a linear increase of electron concentration with height. Figure 2 contrasts the new and existing models with the profiles given by true-height analysis for two sample ionograms. The superiority of the new model, particularly in the height range 150–200 km, is clearly seen and the important difference this creates in assessments of the raypaths over a ground range of 3000 km is also shown in the Figure.

At present, understanding of the reflexion and scattering properties of sporadic-E ionization at h.f. is limited and prediction techniques are restricted to a consideration of its screening effects. Screening is assumed to occur for a wave of frequency $f_{ob}$ incident at an angle $i$ on a patch of sporadic-E ionization when $f$oEs $> f_{ob} \cos i$. The sporadic-E ionization is assumed to be at a constant height of 110 km. As already noted numerical representations of $f$oEs are available.

## 3 Oblique Raypaths

The oblique raypaths are determined by an iterative process which involves supposing a ray is launched in a given direction, tracing its passage via the ionosphere, comparing its ground-arrival position with the desired reception point and using the difference to give a more appropriate launch direction. Current procedures assume great-circle propagation with iteration only in terms of elevation angle. Lateral deviations from the great-circle undoubtedly occur, but it is by no means certain that sufficiently improved prediction accuracies would result from inclusion of estimates of these based on the predicted ionospheric characteristics to justify the added numerical complexity involved.

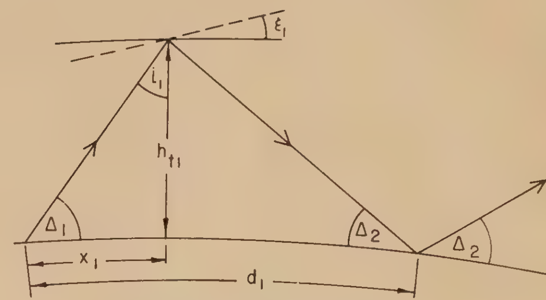


**Fig. 3.** Ray-hop geometry.

In the existing CCIR prediction method a model ionosphere is generated appropriate to the mid-position between transmitter and receiver but the proposed new method[9] involves the generation of a different model ionosphere for each hop of the path. A full ray trace including the effects of the magnetic field is not considered justifiable because of uncertainties in the predictions of the ionospheric conditions but the approximate procedure used allows the effects of longitudinal ionospheric tilts to be incorporated.

The assessment of the active modes and their elevation angles is based on a representation of the raypaths by undeviated propagation between the ground and mirror-reflecting points in the ionosphere. The heights of the mirroring points are taken as the virtual heights of reflexion of waves of 'equivalent' frequency at vertical incidence, and the longitudinal tilts are found from the longitudinal changes in these virtual heights. The layer reflecting each active mode is readily given from the ratio of the vertical-incidence frequency to $f$oE. Consider a ray of frequency $f_{ob}$ launched with elevation angle $\Delta_1$ as indicated in Fig. 3. Suppose that reflexion takes place from a plane reflector at range $x_1$ and of height $h_{t1}$ tilted through an angle $\varepsilon_1$ in the sense shown. Further, let the ray return to ground with elevation angle $\Delta_2$ at range $d_1$. Then if $R$ is the Earth's radius, we have

$$x_1 = R\left[\cos^{-1}\left(\frac{R}{R+h_{t1}}\cos\Delta_1\right) - \Delta_1\right]$$

$$d_1 = 2x_1 + R \times$$

$$\times\left[\Delta_1 - 2\varepsilon_1 - \cos^{-1}\left(\frac{R+h_{t1}}{R}\cos\left[\Delta_1 - 2\varepsilon_1 + \frac{x_1}{R}\right]\right)\right]$$

and

$$\Delta_2 = \Delta_1 - 2\varepsilon_1 + \frac{2x_1 - d_1}{R}$$

Hence with $\Delta_1$, $h_{t1}$ and $\varepsilon_1$ given, $x_1$, $d_1$ and $\Delta_2$ can be determined. $h_{t1} = h'(f_v)$, the virtual height of reflexion at vertical incidence at frequency $f_v$. $f_v$ is given in terms of $f_{ob}$ by

$$f_v = f_{ob} . K . \cos i_1$$

where $i_1$ is the angle subtended to the vertical at height $h_{t1}$ by the upgoing ray and $K$ is an approximate ionosphere and Earth-curvature correction term close to unity and given in terms of $i_1$, $h'(f_v)$ and $h(f_v)$, the true height of

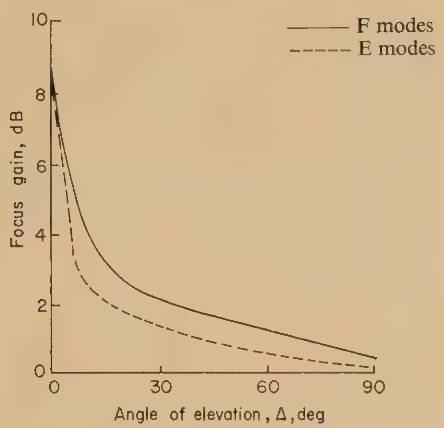


**Fig. 4.** Horizon-focus gain

reflexion at vertical incidence at frequency $f_v$. Relatively simple expressions for $h'(f_v)$ and $h(f_v)$ in the model ionosphere are available. $\varepsilon_1$ is found from the change in $h'(f_v)$ either side of the reflexion point along the great-circle path.

The first estimate of $\Delta_1$ is based on an approximation to the hop length and ionosphere reflecting height. Successive application of the procedure for a specified set of different numbers of hops depending on the great-circle range to the receiver, taking account additionally of the possibility of screening by sporadic-E ionization, enables the active modes and their elevation angles to be determined.

## 4 Transmission-loss Factors

The field strength of a wave at a distance of 1 km from a transmitter radiating $P$ kW isotropically is $173\sqrt{P}$ mV/m. The received signal over an ionospheric path has that strength diminished by

$$(L_S+L_A+L_P+L_E-G_T-G_R)\ \mathrm{dB}$$

where $L_S$ = spatial attenuation

$L_A$ = ionospheric absorption

$L_P$ ≐ polarization coupling and intermediate ground-reflexion losses

$L_E$ = sporadic-E obscuration loss

$G_T$ and $G_R$ = transmitting and receiving aerial gain factors relative to an isotropic aerial along direction of raypath.

### 4.1 Spatial Attenuation, $L_S$

Free-space attenuation, in which the field strength varies in inverse proportion to distance, is allowed for by taking the path length as equal to the mirror-reflecting slant path between transmitter and receiver. No allowance is made for signal focusing at frequencies near the maximum usable frequency because this is a transitory feature likely to be effective only over restricted conditions. However it is proposed to take account in the revised CCIR method of the focusing due to ray convergence of signals with low elevation angles. Figure 4 gives the mean focus gain for E and F modes of propagation deduced for idealized model ionospheres.[15] This gain is independent of the number of wave hops and reaches a maximum of 9 dB at grazing incidence.

### 4.2 Ionospheric Absorption, $L_A$

Waves propagated via the ionosphere are subject to absorption, principally in the D and E regions. Most measurements of this absorption are made at vertical incidence so that for oblique-path predictions it is convenient to first estimate the related absorption at vertical incidence and then to apply a conversion factor to oblique incidence.

It can be shown from magneto-ionic theory that for propagation with a frequency $f_v$ at vertical incidence the absorption of the ordinary wave $L(f_v)$ in decibels is approximately proportional to

$$\int \frac{N\nu}{\mu} \cdot \frac{\mathrm{d}h}{(f_v+f_L)^2}$$

where $N$ is the electron concentration, $\nu$ the electron-collision frequency, $\mu$ the refractive index and $f_L$ the electron gyrofrequency about the vertical component of the Earth's magnetic field. The height limits of the integration are from the base of the ionosphere to the appropriate height of reflexion at frequency $f_v$. Hence the absorption depends on the height distribution of electron concentration. It is referred to as deviative when $\mu \ll 1$ and non-deviative when $\mu \sim 1$. At vertical incidence deviative absorption is large near the height of reflexion when this occurs in the E region. At temperate latitudes in winter the median non-deviative absorption is greater than expected from normal solar control; the day-to-day variability is also large. The effect is referred to as winter-anomaly absorption. At high latitudes there is additional non-deviative absorption known as auroral and polar-cap absorption due to the incidence of solar protons and electrons precipitating from the magnetosphere under disturbed conditions. The absorptions taken into account in the new method of George and Bradley[16] to be used by the CCIR are restricted to normal non-deviative and deviative absorption, together with median winter-anomaly absorption. (The importance of auroral absorption is recognized and it is hoped also to be able to include allowances for this additionally, but the way this will be done is not yet clear.[9])

With the absorption factor $A(f_v)$ defined as

$$A(f_v) = L(f_v).(f_v+f_L)^2$$

the form of its variation with frequency is found to depend only on $f_v/f\mathrm{oE}$.

Taking

$$\frac{A(f_v)}{A_T} = \varphi_n\left(\frac{f_v}{f\mathrm{oE}}\right)$$

where $A_T$ is the limiting value of $A(f_v)$ for a frequency sufficiently high that the signals traverse the whole of the absorbing region without deviation, the function $\varphi_n$ is approximately independent of location, season or solar epoch and is given in Fig. 5. $\varphi_n$ increases with increase of $f_v/f\mathrm{oE}$ as the depth of ray penetration increases, and it reaches a maximum around $f_v = f\mathrm{oE}$ when there is a large amount of deviative absorption in the E region. From the curves of Fig. 5 for $\varphi_n$ and empirical expressions

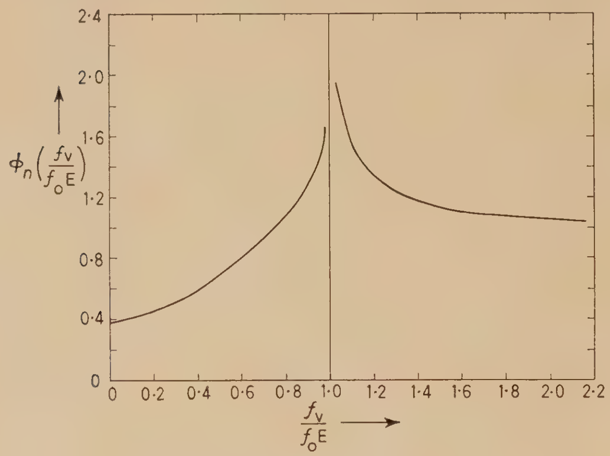


**Fig. 5.** The absorption factor $\varphi_n(f_v/f$oE).

derived from measurements for the diurnal and solar-cycle variations of the absorption, absorption data measured at different locations and frequencies have been used to produce a world map of $A_T$—(Fig. 6). The absorption at vertical incidence can be deduced for any frequency, place and time by using this map in conjunction with the curves for $\varphi_n$ and the expressions giving the diurnal and solar-cycle variations.

The absorption at oblique incidence is increased over that at vertical incidence because of the increased raypath length through the slab of absorbing ionization. However, when making the conversion from vertical to oblique incidence it is necessary to relate the absorptions at 'equivalent' frequencies having the same heights of layer penetration and same fractions of deviative absorption. Then, if $A(f_{ob})$ is the absorption factor at frequency $f_{ob}$ of an oblique ray incident at angle $i$

$$A(f_{ob}) = A(f_v) \sec i$$

Using ray-tracing calculations of absorption for a range of model ionospheres simple empirical expressions have been found for the height at which $i$ is to be determined and for $f_v$ in terms of $f_{ob}$.

### 4.3 Polarization Coupling and Intermediate Ground-reflexion Losses, $L_P$

In general when an upgoing wave is incident on the ionosphere it leads to the excitation of an ordinary (O) and an extraordinary (X) wave. These two waves have different polarizations, and may be regarded as propagating independently within the ionosphere with different absorptions. Ground-reflexion losses depend on wave polarization and so differ for downcoming O and X waves. Hence it is convenient to examine polarization-coupling losses, multiple-hop ground losses and absorption losses together.

First consider single-hop propagation over a path as shown in Fig. 7(a) between a transmitter at T and receiver at R. A and B are the positions of wave entry to and exit from the ionosphere respectively. The wave launched at T travels through the free space to A with unchanged polarization. At A elliptically polarized O and X waves are excited and these are propagated independently along closely similar raypaths to B. (In the Figure, the separation of the raypaths is accentuated for clarity.) At all

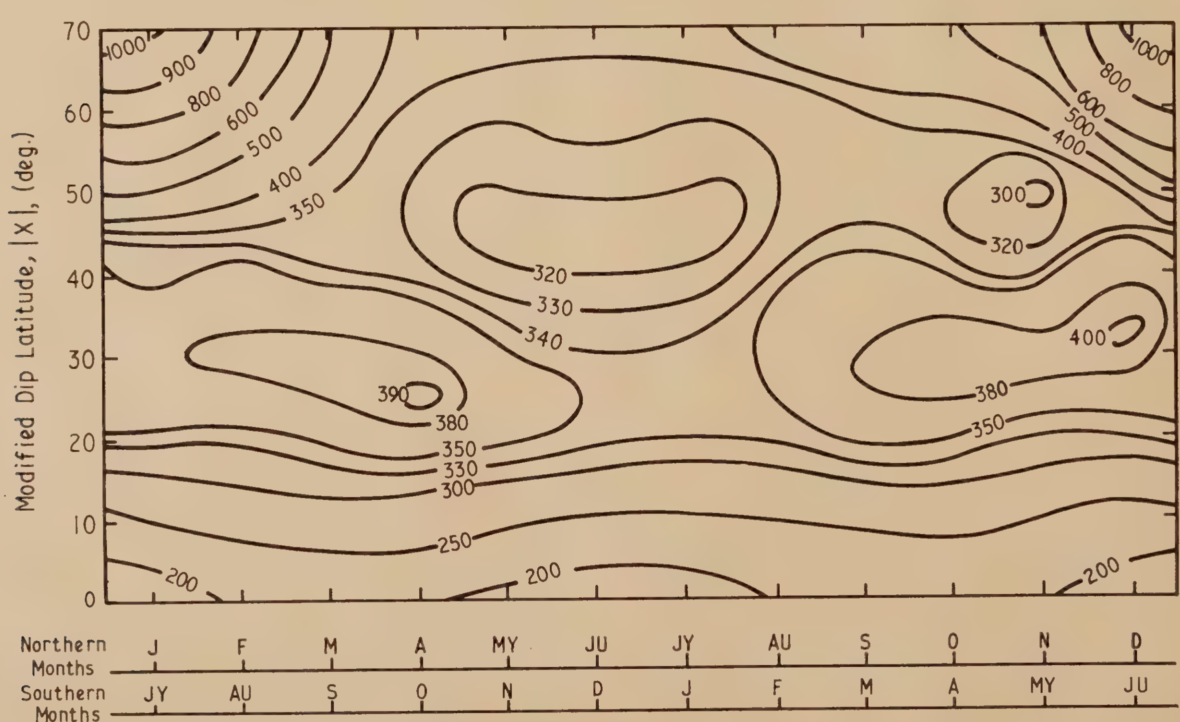


**Fig. 6.** The absorption factor $A_T$ for an overhead sun and a smoothed-sunspot number of zero.
Modified dip latitude $X$ is defined as $X = \arctan I/\sqrt{\cos \lambda}$
where $I$ = magnetic dip in radians and $\lambda$ = geographic latitude

positions along the raypaths in the ionosphere the O and X wave polarizations change, but between B and R the wave polarizations are constant and equal to the so-called limiting polarizations at B. The fractions of power coupled to the O and X waves and the fractions of power in the downcoming waves coupled to the receiving aerial at R depend on the limiting polarizations of the O and X waves at A and B, on the polarization of the wave radiated from the transmitter, and on the polarization to which the receiving aerial responds.

In the existing CCIR prediction method polarization-coupling loss is taken into account indirectly by an empirical allowance. In the proposed new method it will be specifically evaluated using the expressions of Moorat.[17] These apply provided that the transmitting and receiving aerials radiate and respond to waves which are either horizontally or normally (vertically) polarized; this restriction is not serious because most aerials on h.f. point-to-point circuits operate in this way. Standard equations are available for the power coupling between waves of different polarization, and limiting polarization is deduced from magneto-ionic equations, assuming it to be equal to the characteristic wave polarization at a low height where the electron concentration and electron collisions may be neglected. The limiting polarization is then a function of the wave direction and frequency and the magnetic-field direction and intensity. The downcoming waves propagated as O and X waves within the ionosphere are assumed to have random relative phases so that their mean received powers are additive. These powers are summed after allowing for the differences in ionospheric absorption. The absorption of the X wave $L_X$ dB is assumed to be related to that of the O wave $L_O$dB by

$$L_X(f-f_L)^2 = L_O(f+f_L)^2$$

When propagation is quasi-longitudinal to the Earth's magnetic field the limiting polarizations are circular, and

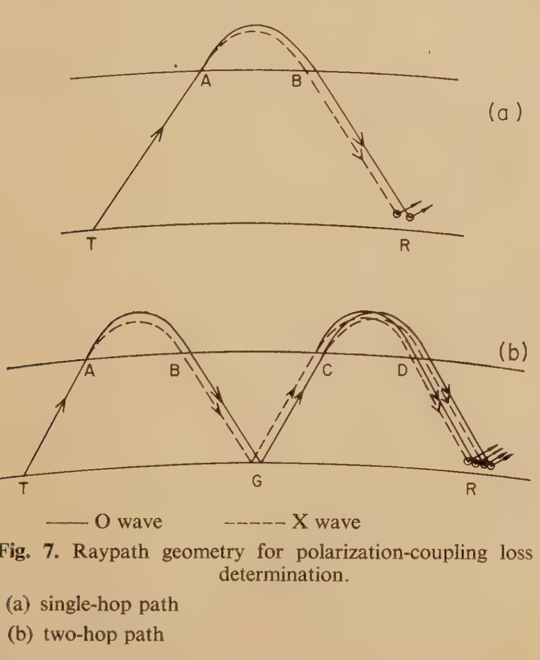


**Fig. 7.** Raypath geometry for polarization-coupling loss determination.

(a) single-hop path

(b) two-hop path

the effective polarization-coupling loss ranges from 3 to 6 dB depending on the differential absorption of the X wave relative to the O wave. However, under other propagation conditions polarization-coupling losses of up to 20 dB can occur, confirming the importance of including the full calculation.

Additional calculations are necessary for multiple-hop modes to take account of the loss of power at ground reflexion and of the effective transfer of power between the O and X waves on successive hops arising from the mode conversion which takes place at each entry to the ionosphere.[18] Consider propagation via a two-hop mode as shown in Fig. 7(b). At B there are in general two downcoming elliptically polarized waves which suffer a loss of power and change of polarization at ground reflexion. Each of the corresponding elliptically polarized upgoing waves is split at C into O and X wave components. There are thus at D two component waves with an O wave limiting polarization and two with an X wave limiting polarization. The components with like polarization have random relative phases and so may be combined to give a resultant wave of the same polarization with a power equal to the sum of the powers of the components. The received power at R from the downcoming O and X waves at D is then determined as in the single-hop case. The loss of power and change of polarization at ground reflexion are functions of the Fresnel reflexion coefficients for horizontally and normally polarized incident waves. These are given in terms of wave frequency, elevation angle, ground conductivity $\sigma$ and dielectric constant $\kappa$ where $\sigma$ and $\kappa$ are specified from a numerical representation of a map of land-sea boundaries.

### 4.4 Sporadic-E Losses, $L_E$

Sporadic-E consists of thin sheets of enhanced ionization embedded in the regular E layer. Each sheet is composed of a number of separate blobs having a range of different electron concentrations, so that there is no single frequency at which a given sheet becomes opaque to radio waves. In so far as the ionospheric characteristic $f$oEs is a measure of the mean maximum plasma frequency of the sheet as a whole it is to be expected that the sporadic-E obscuration losses for a wave of frequency $f_{ob}$ incident at an angle $i$ will be some function of $f_{ob}\cos i/f$oEs, where the absolute loss and its dependence on $f_{ob}$ are related to the spatial distribution and range of electron concentrations of the individual blobs. The present CCIR prediction method does not include an allowance for $L_E$ but it is anticipated that an internationally agreed expression will be produced within the next year based on work by Miya and Sasaki[19] in Japan and investigations being carried out in the U.S.A.

### 4.5 Transmitting and Receiving Aerial Gain Factors, $G_T$ and $G_R$

Theoretical expressions for $G_T$ and $G_R$ have been produced and collated by Ma and Walters[20] for a range of different basic aerial types. These give the gain factors in any selected direction as a function of wave frequency and aerial element sizes, positions and orientations. Account is taken of the imperfect ground by specifying

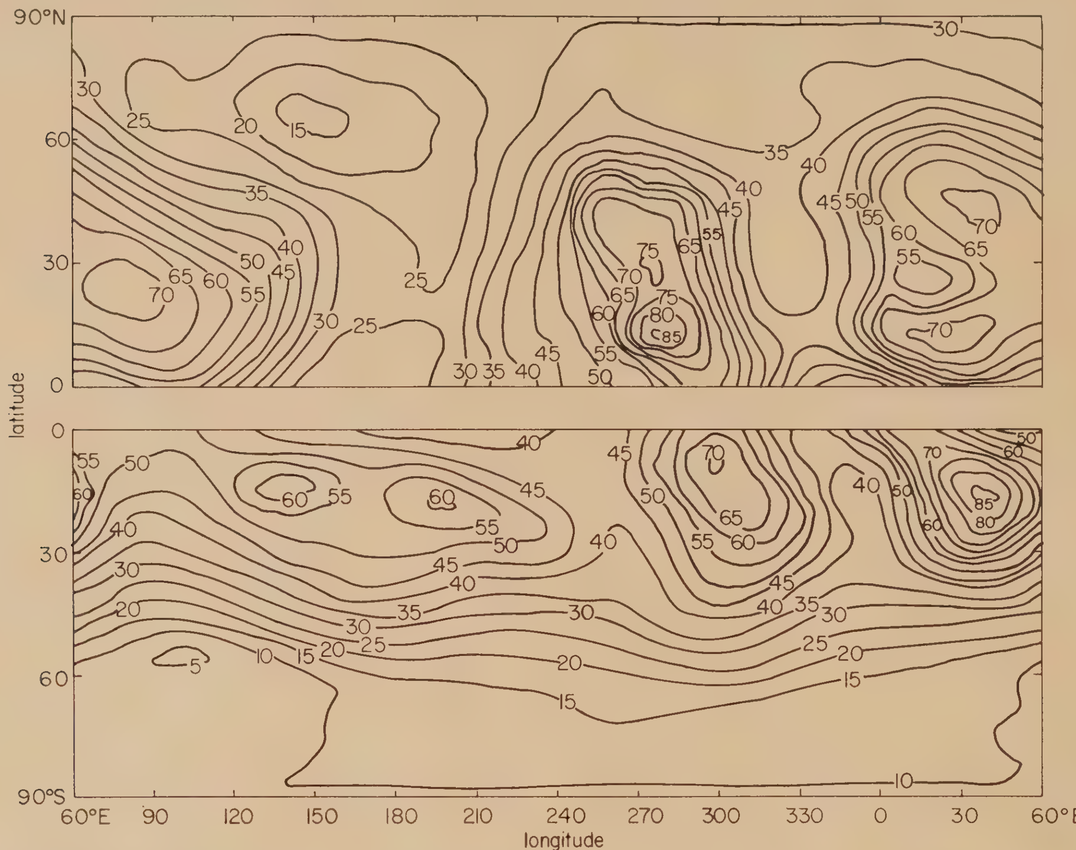


**Fig. 8.** $F_{am}$, expected atmospheric noise power at receiver at 1 MHz in summer at 12–16 hours local time, dB above $kT_0B$ where $T_0$ is the reference temperature of 288 K.

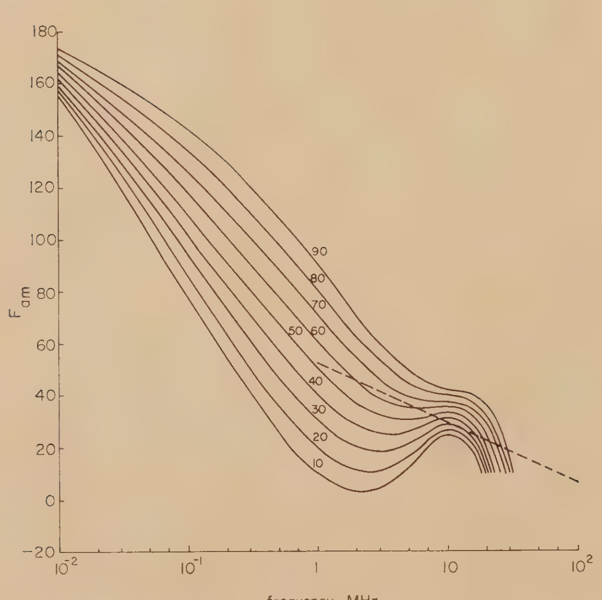


**Fig. 9.** Expected variation of atmospheric noise power at receiver with frequency in summer at 12–16 hours local time
----- expected cosmic noise in the absence of ionospheric screening.

the ground conductivity and dielectric constant. This set of expressions will be included in the new version of the CCIR field-strength prediction method.

## 5 Background Noise

The background noise against which the wanted signals must compete includes atmospheric noise from thunderstorms, man-made noise, other radio transmissions, cosmic noise and receiver noise. At h.f. it is rare to find receiver noise dominant and cosmic noise is usually only important in quiet locations at the upper frequencies of the band.

Atmospheric noise exhibits well-defined geographical and temporal variations and its dependence on frequency and receiver bandwidth have been extensively studied using data from measurements made with short vertical receiving aerials. Maps of measured atmospheric noise intensities have been produced for different seasons and times[21] and an example of one such map is presented in Fig. 8 which gives the noise power at a frequency of 1 MHz; Fig. 9 gives a means for estimating the corresponding noise at other frequencies. Also shown in Fig. 9 for comparison is the expected cosmic-noise intensity in the absence of ionospheric screening. Since well-established and generally applicable trends in the year-to-year changes in atmospheric noise have not been found and since to a first-order received atmospheric noise powers using directional or omnidirectional aerials are similar, these maps are the most appropriate for use

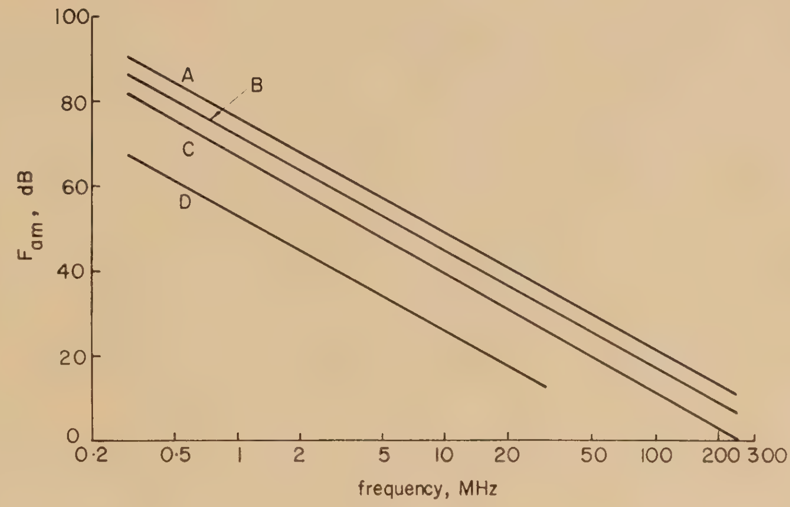


**Fig. 10.** Mean values of man-made noise power at receiver for a short vertical loss-less grounded monopole aerial situated in different areas
A business C rural
B residential D quiet rural

in the prediction method. They have been represented in numerical form by Zacharisen and Jones.[22]

Man-made noise results from a variety of sources such as motor-car ignition systems, commutator and industrial machinery, neon and fluorescent lights, hospital therapy equipment, corona discharge from electrical transmission lines, etc., and so is very variable in nature. There is, however, some evidence of a correlation of likely intensities with degree of urbanization, and the CCIR now proposes four basic man-made noise curves for business, residential, rural and quiet rural areas.[23] (Fig. 10.) In the interests of keeping transmitter powers to a minimum every effort should be made wherever possible to locate receiving sites in quiet rural areas.

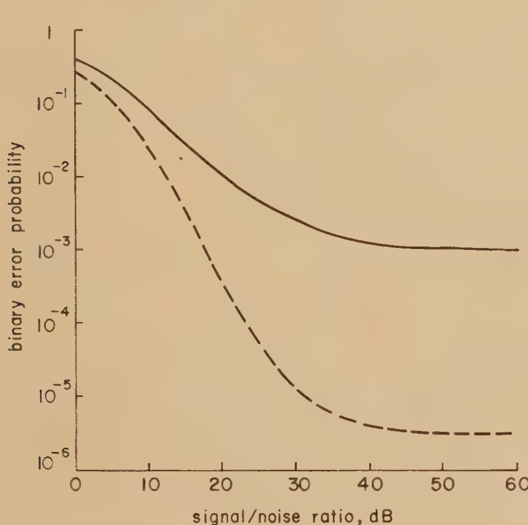


**Fig. 11.** Binary error probability as a function of signal/noise ratio for f.s.k. transmissions with data rate of 100 baud via medium with time dispersion of 1 ms and frequency dispersion of 1 Hz (from ref. 26).
——— no diversity
– – – – dual diversity (that is, system using space, polarization or frequency diversity).

Whilst undoubtedly other radio transmissions can impose an over-riding restriction on satisfactory signal reception, such considerations should not be allowed to influence system design, lest a general world-wide escalation of transmitter powers ensues. Where such interference is found to exist after a system has been installed, the solution lies in a re-allocation of frequency of one of the transmitters. Such problems must be resolved by the International Frequency Registration Board in conjunction with the appropriate national authorities—in the United Kingdom, the Home Office.

## 6 Radio-circuit Design

The type of information to be conveyed over the proposed circuit and its required data rate determine the necessary receiver bandwidth and modulation system. The next step in the circuit design is to specify the wanted signal/noise ratio at the receiver. Minimum signal/noise ratios judged to give satisfactory signal reception with different classes of emission have been determined.[24, 25] For circuits transmitting data a more sophisticated assessment may be made using relationships between data error rate and signal/noise ratio based on results of laboratory simulations for different types of modulation systems.[26] Figure 11 shows that error rate decreases with increase of signal/noise ratio only up to some limiting value determined by the signal distortion introduced in the ionosphere. Signal distortion arises from: (i) time dispersion—due to multiple modes, high and low-angle rays, ordinary and extraordinary waves, or scattered signals and (ii) frequency dispersion—due to movements or changes in ionization. The effects of signal distortion can, to some extent, be reduced by using space, polarization or frequency diversity receiving systems. From a general consideration of the geographical area through which the circuit will pass, i.e. equatorial, temperate, auroral or polar, the likely signal distortion may be estimated and, having regard to available resources, a decision made whether to build a diversity system. With the maximum permissible error rate given, the required signal/noise ratio may be deduced from curves similar to those of

```
                                        1
             JUNE 15, 1966       10 CM FLUX  98.      (SSN  45.)
     LERWICK      TO          SLOUGH                  AZIMUTHS       MILES        KM.
60.15N -    1.15W      51.50N -    0.60W      177.72  358.18        598.1        962.5
                                    MINIMUM ANGLE  0.0 DEGREES
XMTR  2.0 TO 30.0  CONSTANT GAIN  H   0.00 L    0.00 A    0.0 OFF AZ    0.0
RCVR  2.0 TO 30.0  CONSTANT GAIN  H   0.00 L    0.00 A    0.0 OFF AZ    0.0
POWER=    2.00KW   3 MHZ NOISE=-148.0DBW  TIME= 90 PERCENT   REQ.S/N=45.0DB
MULTIPATH POWER TOLERANCE= 6.0 DB      MULTIPATH DELAY TOLERANCE=0.50 MS.
                                    FREQUENCIES IN MHZ
UT    MUF   2.0   3.0   5.0   7.0   9.0   12.0  15.0  18.0  22.0  26.0  30.0

04    6.9   K(0)MUF=( 8.2)    K(5)MUF=( 5.5)
      1F    1E    2F    1F    1F    -     -     -     -     -     -     -     MODE
      35.6  8.5   48.2  28.5  35.6  -     -     -     -     -     -     -     ANGLE
      .50   .99   .99   .99   .47   -     -     -     -     -     -     -     F. DAYS
      31.   13.   22.   30.   31.   -     -     -     -     -     -     -     DBU
      64.   42.   53.   62.   64.   -     -     -     -     -     -     -     S/N DB
      .43   .40   .70   .83   .41   -     -     -     -     -     -     -     REL.
      -     .34   .64   .79   -     -     -     -     -     -     -     -     MP PROB

08    9.9   K(0)MUF=( 9.9)    K(5)MUF=( 9.9)
      1E    -     -     2F    1F    1E    -     -     -     -     -     -     MODE
      11.9  -     -     47.4  27.5  10.1  -     -     -     -     -     -     ANGLE
      .99   -     -     .99   .99   .99   -     -     -     -     -     -     F. DAYS
      23.   -     -     7.    22.   19.   -     -     -     -     -     -     DBU
      64.   -     -     40.   57.   63.   -     -     -     -     -     -     S/N DB
      .88   -     -     .33   .79   .86   -     -     -     -     -     -     REL.
      .10   -     -     -     -     -     -     -     -     -     -     -     MP PROB

12    11.5  K(0)MUF=(11.5)    K(5)MUF=(11.5)
      1E    -     -     -     1F    1E    -     -     -     -     -     -     MODE
      11.9  -     -     -     28.3  9.4   -     -     -     -     -     -     ANGLE
      .99   -     -     -     .99   .99   -     -     -     -     -     -     F. DAYS
      21.   -     -     -     18.   11.   -     -     -     -     -     -     DBU
      56.   -     -     -     52.   60.   -     -     -     -     -     -     S/N DB
      .81   -     -     -     .75   .90   -     -     -     -     -     -     REL.
      -     -     -     -     -     -     -     -     -     -     -     -     MP PROB

16    10.5  K(0)MUF=(10.5)    K(5)MUF=(10.5)
      1E    -     -     2F    1F    1E    -     -     -     -     -     -     MODE
      11.9  -     -     48.3  28.5  9.8   -     -     -     -     -     -     ANGLE
      .99   -     -     .99   .99   .99   -     -     -     -     -     -     F. DAYS
      24.   -     -     7.    22.   19.   -     -     -     -     -     -     DBU
      58.   -     -     40.   57.   62.   -     -     -     -     -     -     S/N DB
      .81   -     -     .29   .82   .88   -     -     -     -     -     -     REL.
      .02   -     -     -     -     -     -     -     -     -     -     -     MP PROB

20    10.2  K(0)MUF=(10.2)    K(5)MUF=(10.2)
      1F    1E    1F    1F    1F    1F    1F    -     -     -     -     -     MODE
      32.8  8.5   29.5  26.5  26.9  28.6  32.8  -     -     -     -     -     ANGLE
      .50   .99   .99   .99   .67   .79   .05   -     -     -     -     -     F. DAYS
      30.   8.    24.   27.   29.   30.   30.   -     -     -     -     -     DBU
      62.   36.   53.   57.   59.   61.   63.   -     -     -     -     -     S/N DB
      .44   .18   .73   .80   .81   .68   .05   -     -     -     -     -     REL.
      -     .15   .58   .71   .50   .02   -     -     -     -     -     -     MP PROB

24    8.0   K(0)MUF=( 8.0)    K(5)MUF=( 8.0)
      1F    1F    1F    1F    1F    1F    -     -     -     -     -     -     MODE
      34.1  29.0  28.1  28.6  30.1  34.1  -     -     -     -     -     -     ANGLE
      .50   .99   .99   .95   .74   .22   -     -     -     -     -     -     F. DAYS
      34.   29.   31.   33.   34.   34.   -     -     -     -     -     -     DBU
      64.   54.   56.   60.   62.   65.   -     -     -     -     -     -     S/N DB
      .44   .73   .78   .80   .65   .20   -     -     -     -     -     -     REL.
      -     .62   .68   .62   .08   -     -     -     -     -     -     -     MP PROB
```

**Fig. 12.** Sample computer print-out of propagation predictions for path Lerwick (Shetland Islands) to Slough (England) in June 1966.

Fig. 11. Propagation predictions may then be examined as described below to see how this signal/noise ratio can be achieved.

Using a computer program to carry out the stages of calculation described in Sections 2–5 it is convenient to first assume the use of isotropic transmitting and receiving aerials and a reference transmitter power. Figure 12 shows a sample prediction for a range of hours in a given month based on the prediction method in current use by the CCIR.[8] Such predictions would be repeated for a selection of months and levels of solar activity over which it is proposed the circuit should operate. The predictions relate to a range of nominal wave frequencies and give for each:

(i) the dominant propagation mode;

(ii) its angle of elevation (in this case assumed the same at transmitter and receiver, degrees);

(iii) the fraction of days that it is predicted as active (deduced assuming a given statistical variation of the day-to-day maximum plasma frequencies about the monthly median values);

(iv) the median signal strength (dB above 1 μV/m);

(v) the median signal/noise ratio (dB);

(vi) the reliability (The fraction of days that the dominant mode is active and has the desired signal/noise ratio and multipath tolerance. This assumes a given statistical law for the day-to-day variations in signal transmission loss relative to the predicted median loss.)

A histogram of elevation angles of the dominant mode serves to define the required aerial characteristics. A similar histogram of the frequencies with the greatest reliability indicates the range of frequencies for which the circuit should be engineered. Hence the design of the optimum aerials can be specified. Repetition of the calculations assuming the use of optimum aerials and for a range of transmitter powers then leads to a relationship between overall service probability (the fraction of time the desired reliability is achieved) and transmitter power, from which the necessary power to achieve the desired service probability can be determined.

## 7 Concluding Remarks

To the uninitiated the steps outlined may appear complex and fraught with possible errors. Nevertheless it is the opinion of the CCIR that, to establish a reliable communication circuit, predictions of this general type should be undertaken. The design of any communication system must be an engineering compromise between reliability and complexity (i.e. cost) determined from considerations of the importance of the system to the user. Once such a system has been built there remains the problem of selection of operational frequencies for specific occasions. This subject is considered in companion papers of this issue of *The Radio and Electronic Engineer*.

## 8 Acknowledgement

This paper is published with the permission of the Director of the Appleton Laboratory.

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* These documents were approved at the Final Meeting of the CCIR Study Group 6 in February 1974, preparatory to the CCIR XIIIth Plenary Assembly to be held in 1974, and, when ratified by that Assembly, will be published by the International Telecommunication Union.

*Manuscript first received by the Institution on 10th May 1974 and in final form on 23rd July 1974* (*Paper No. 1622/Com 102.*)

UDC 341.226: 551.510.5

# The CCIR and the ionosphere

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SUMMARY

A brief history is given of the CCIR with its Study Group structure, in particular Study Group 6 on 'Ionospheric Propagation'. The system of documentation is described with special reference to the Reports which form a most valuable source of information on ionospheric propagation in relation to radio communication. The nine Working Groups under which the work of Study Group 6 is organized at the Interim and Final Meetings are considered in turn, and reference is made to the cooperation with URSI in the more scientific aspects of the work. The part played by the CCIR as a subsidiary body of the ITU is explained in providing the basic information required by the IFRB and the planning experts at ITU Conferences.

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## 1 Introduction

From the early days of radio it was realized that the upper atmosphere must be in some manner conducting, so that radio waves can be reflected from it and returned to Earth, thereby accounting for propagation to great distances round the curve of the Earth. Indeed it was by the use of radio waves that direct evidence of the ionosphere was found by interference between the ground and reflected waves in the frequency-change experiments of Appleton and his co-workers, and by the observation of pulse reflexions by Breit and Tuve.

It was soon appreciated that the successful use of radio waves for communications for long distances depended on a knowledge of the structure of the ionosphere and the nature of its diurnal, seasonal and secular variations, leading to the complementary use of radio as a tool for studying the ionosphere. It was also clear that international cooperation was essential, whether the primary interest was in the communications or the ionosphere itself. Thus it is fair to say that although Appleton made a major contribution to the magneto-ionic theory of propagation, his main study was the morphology of the ionosphere, being one of the founders of the International Union for Radio Science (URSI) where the emphasis is naturally on the physics of the ionosphere and latterly of the magnetosphere.

On the other hand in radio communications there are many practical problems arising from the irregularities in the structure of the ionosphere and from the occurrence of disturbances which give rise to the distortion and fading of signals, together with interference from atmospheric noise and between transmissions on the same or neighbouring frequencies. Such matters come within the province of the International Telecommunication Union (ITU) in framing the Radio Regulations which, amongst other things, are concerned with the division of the radio frequency spectrum into bands for the various services. The technical examination and recording of specific frequencies within these bands is the function of the International Frequency Registration Board (IFRB). To aid in this work the ITU set up a Consultative Committee of International Radio (CCIR) to provide the scientific information upon which technical decisions may be based.

## 2 Brief History of the CCIR

The CCIR had its origins in the period between the two World Wars, but as a result of the ITU Conference at Atlantic City in 1947 it was reorganized at the Vth Meeting at Stockholm in 1948. The work is divided among a number of Study Groups which were modified somewhat at the IXth Plenary Assembly at Los Angeles in 1959 and again at the XIIth Plenary Assembly at New Delhi in 1970. They deal with various aspects of radio usage such as sound and television broadcasting, fixed and mobile services, standard frequencies and time signals, space research and radio astronomy and communication satellites, but Study Groups 5 and 6 have a special place since they provide the basic scientific information upon which much of the work of the other Study Groups depends.

Study Group 5 deals with propagation in non-ionized media including the troposphere and outer space, but here the particular interest is in Study Group 6 entitled 'Ionospheric Propagation'. It is mainly concerned with terrestrial propagation by the ionosphere at frequencies below about 30 MHz, but it takes account of the fact that the effect of the ionosphere can extend well into the v.h.f. band and to much higher frequencies, since radio waves from Earth stations to outer space have to pass through the ionosphere.

Between the Plenary Assemblies of the whole CCIR, which take place at approximately three-year intervals, the individual Study Groups hold an Interim Meeting and a Final Meeting at international level at which the documents contributed by the separate Administrations and Member Organizations form the material for the revision of the CCIR Volumes from one Plenary Assembly to the next. There are now seven such Volumes and the one containing the documentation of Study Group 6 is Volume II, Part 2.† Collectively they are known popularly as the CCIR Green Books (English edition). At the time of writing the Final Meetings prior to the XIIIth Plenary at Geneva in July 1974 have been held, but an interval of some months must elapse before the new Green Books are published.

## 3 CCIR Documentation

In principle the work of the Study Groups is based on a number of Questions, and to aid in answering them Study Programmes are set up which result in most cases in Reports. The ultimate aim is to express the findings in Recommendations for certain specific actions. It may be noted that these are not mandatory in the sense that the Radio Regulations are to the member Administrations of the ITU, but they are often quoted as requirements in specifications for the design and production of radio equipment.

Two further types of CCIR documents are Resolutions and Opinions which are of less weight than the Recommendations. As far as Study Group 6 is concerned, the Resolutions are mainly for the setting up and continuance of Interim Working Parties (IWP). These are small groups appointed by the Study Groups to carry out special tasks. They are international, the members being chosen by the Administrations which express a desire to participate in their work, which is done mainly by correspondence and presented at the Interim and Final Meetings of the whole Study Group.

Study Group 6 has set up eight such IWPs, though it is now proposed that two of them shall be terminated. It has only six Recommendations, three of which refer directly to the use of information contained in Reports. On the other hand there are over thirty Reports, so that it is clear that these together constitute a very valuable store of information on radio propagation and its application to communications. They are of particular interest to countries which have not ready access to the vast literature of the subject from which much of the information has been taken and to which many references are given.

† CCIR XIIth Plenary Assembly. New Delhi 1970.
Vol. II Part 2. Ionospheric Propagation (Study Group 6).
Published by the International Telecommunication Union, Geneva, 1970.

## 4 Organization of Study Group 6 Work

For many years the work carried out at the Interim and Final Meetings has been organized in nine Working Groups, 6A to 6H together with 6S added to deal with topics of space. Their titles, as set out in the New Delhi Green Book, are given in the following sub-sections where their work is discussed in turn. 6A, 6B and 6E deal more directly with the ionosphere itself as expressed in terms of the parameters that are important in ionospheric propagation. 6C and 6G are concerned with the estimation of field strengths in the frequency bands used in terrestrial communications, making use of the ionospheric data dealt with by 6A, 6B and 6E. 6F discusses in a general way the interference between radio communications due to irregular or abnormal modes of propagation, and is to some extent allied to 6D and 6H dealing respectively with noise and fading and their adverse effect on radio communications.

It is not proposed here to discuss the Questions and Study Programmes upon which the work depends, but to concentrate on the resulting body of Reports and the related Resolutions and Recommendations. In the following surveys of the Working Groups it is assumed that those interested in further details will have access to the New Delhi Green Book and in due course to the Geneva 1974 Green Book that will supersede it.

### 4.1 Ionospheric and Solar Indices (Working Group 6A)

Working Group 6A has two Recommendations, one dealing with international cooperation in the exchange of ionospheric information concerned with short-term forecasts and ionospheric disturbance warnings, and the other on the choice of basic indices for ionospheric propagation. They are supported by four Reports, one of which gives a list of organizations concerned with the exchange of data and the issuing of forecasts on propagation conditions, while two others deal with the prediction of the solar index and the choice of basic indices.

In an accompanying Resolution the Director of the CCIR is requested to make arrangements to obtain the most recent data on solar indices and the monthly median values of ionospheric data, and to calculate the monthly values of the indices. IWP 6/7 has been set up to study short-term predictions of operational parameters for ionospheric radio communications.

### 4.2 Prediction of M.U.F. (Working Group 6B)

The one Recommendation of Working Group 6B is concerned with the definitions of the maximum usable frequency (m.u.f.) according to the conditions to which they apply, and there is a Report on maximum transmission frequencies that sets out the definitions in detail. Five other Reports deal with ionospheric sounding at oblique incidence, the application of basic prediction

information to propagation, and the phenomena of back scattering, side scatter and long-distance propagation without intermediate ground reflexion.

### 4.3 Field Strengths between about 1·5 and 40 MHz (Working Group 6C)

The major task of Working Group 6C is the development of a method for estimating sky-wave field strengths in h.f. propagation. One Report discusses the systematic measurements of field strengths to obtain a mass of practical information by which a proposed prediction method can be assessed. The study has been proceeding for more than twenty years and many different proposals have been put forward by various Administrations. Basically they depend on multiple-hop propagation using ray theory with an assumed model of the ionosphere.

With the advent of modern computing methods it has become practicable to use the detailed ionospheric information with which Working Groups 6A, 6B and 6E are concerned, and a provisional method has been given in Report 252-2. The number is quoted here, since in view of its length the Report has been published separately from the Green Book itself. In it an attempt has been made to coordinate the various methods referred to above and it includes a detailed computer program.

It has been prepared largely by IWP 6/1 and it has not yet been made the subject of a Recommendation as it is still under major revision, particularly as a result of discussions at the recent Final Meeting of Study Group 6. Instead, a Resolution requests that Administrations should evaluate this interim method of field-strength estimation against their own experimental observations and different needs. It has been suggested that the Resolution should be replaced by an Opinion in view of the present position.

### 4.4 Atmospheric and Man-made Radio Noise (Working Group 6D)

In view of the interference aspect of atmospheric radio noise and its influence on the minimum field strength required for a given circuit in ionospheric propagation, its measurement and the determination of its world-wide distribution as a function of time of day, season and solar cycle are very important factors in ionospheric propagation. Working Group 6D has a Report on the measurement of atmospheric radio noise that discusses the network of measuring stations with the methods of measurement, including the use of lightning-flash counters and directional antennae.

On the basis of the measurement campaign, a Report 322 has been prepared by IWP 6/2. In view of its length it has also been published separately, and it includes many maps of the world distribution and characteristics of the noise. There is a Recommendation that states that the Report should be used until new data have been accumulated justifying its revision.

Unfortunately it is unlikely that in the near future effort will be available for the undertaking of this task, and it is now proposed to discontinue the IWP and to delete the Resolution by which it was set up and maintained. The Working Group has also produced a Report on the measurement of man-made noise as a cause of interference when it is received by ionospheric propagation.

### 4.5 Ionospheric Mapping (Working Group 6E)

The Working Group 6E is closely related to 6A and 6B, but its special purpose is the mapping of ionospheric characteristics. A Report deals with the problem of improving the world-wide ionospheric observing programme, including the use of top-side sounding and other satellite data for numerical mapping purposes. IWP 6/3 has prepared an Atlas of ionospheric characteristics which with a supplement to its original form is published separately as Report 340–1. Special stress is laid on the availability of a punched card form of the Atlas in a Recommendation that the Atlas with any further revisions should be used by international organizations, and also by the IFRB for the solution of ionospheric problems, the cards and computer programme being available for distribution by the Director of the CCIR.

### 4.6 Problems of Interference (Working Group 6F)

The problems of interference in ionospheric propagation are described by Working Group 6F in a series of Reports on

(a) intermittent communication by meteor-burst propagation,

(b) v.h.f. propagation by way of sporadic E and other anomalous ionization,

(c) ionospheric-scatter propagation,

(d) h.f. propagation by ducting above the maximum of the F region,

(e) special problems of h.f. radio communication associated with the equatorial ionosphere, and

(f) the prediction of sporadic E.

To some extent these topics overlap with those of 6B and 6E and depend upon the information in the Reports of 6A. Thus a matter of increasing importance is the extent to which sporadic E and the structure of the equatorial ionosphere can be predicted, especially on a daily basis, so that they can be included in ionospheric mapping and taken into account, not only as sources of interference, but as propagation mechanisms in h.f. communications. IWP 6/8 is in fact concerned with v.h.f. propagation by sporadic E. Furthermore, communication systems have been established using meteor-burst propagation and ionospheric forward scattering, even though they have been mainly limited to rather specialized and sophisticated uses. The possibility of h.f. propagation in ionospheric ducts in the upper part of the ionosphere is of possible interest in space communications, but as in propagation in a tropospheric duct, such ducts could be a source of interference where frequency sharing is based on the assumption that they do not occur.

### 4.7 Field Strengths below about 1·5 MHz (Working Group 6G)

It is well known that medium frequencies cannot be propagated by way of the ionosphere during daylight because of heavy absorption in the D region, but that circuits planned to operate on the groundwave suffer

interference at the greater distances by reflexions from the E layer at night. Beyond the groundwave range the ionospheric propagation of medium frequencies then becomes an important communication mode, especially in sparsely populated regions for information not demanding high-fidelity reproduction. The problems of medium frequency broadcasting involve difficult frequency sharing considerations, so that it is essential to establish a method of estimating nighttime field strengths.

So far this has been done on an almost completely empirical basis by fitting a formula to a mass of experimental data obtained in a field-strength measurement campaign in the European Broadcasting Area over a period of about ten years. This method has been described by Working Group 6G in a Report that forms the basis of a Recommendation for its provisional use in the Area. It is known that especially at the higher frequencies in the medium-frequency band the curves underestimate the field strengths at the larger distances beyond 3000 km and that they do not apply in some other areas of the world.

Ideally the estimation should be based on wave theory for multiple-hop propagation in a similar way to that adopted for high frequencies by IWP 6/1 and great progress has been made in this direction. However, because of the complexities of the method, including the major effect of the Earth's magnetic field, the effects of ground reflexions and polarization-coupling loss, and the dependence of the absorption on the model of the ionosphere assumed, improved predictions with their extension to other parts of the world are still to be based on a semi-empirical approach using experimental data.

IWP 6/4 has recently put forward for adoption by the Plenary Assembly such a revision designed for world wide application, using a formula with parameters that can be adjusted to fit the data for different regions of the world. It is to be hoped that it can be accepted with a view to its use by the IFRB and the planning experts for the forthcoming M.F. and L.F. Broadcasting Conference.

Working Group 6G has also Reports describing the work being done on m.f. field strengths in various countries and on the accuracy of field-strength predictions in the m.f. and l.f. bands, while a long Report discusses the problem of sky-wave propagation at frequencies below 150 kHz where a full-wave treatment has to be used. This latter study is extremely erudite and it is being pursued by IWP 6/5 working as a small team of scientific experts. A new Report has been prepared on ionospheric cross-modulation, giving a simplified account of the scientific basis of the phenomenon and an estimate of it as a source of interference in broadcasting.

### 4.8 Fading of Signals Received via the Ionosphere (Working Group 6H)

Working Group 6H has a Report on fading and IWP 6/6 has from time to time revised it to make it more useful to the radio engineer. It is now felt that further revision in the near future is unlikely and it is proposed to discontinue the IWP and delete the associated Resolution. The Report is mathematical in its approach, but it considers in turn the causes of fading, short and long period variations, and space, time, frequency and polarization diversity.

### 4.9 Topics Related to Space Systems (Working Party 6S)

With the advent of Earth–space communications and the requirements of high precision in position and time, it was realized that even at the very high frequencies involved, the ionosphere can have important effects on the waves passing through it. These are discussed in a Report which deals with scintillation effects, Faraday rotation of the plane of polarization, and group delay, phase–path length and refraction as a function of frequency. Working Group 6S in another Report considers the important subject of radio noise within and above the ionosphere.

A third Report discusses v.l.f. propagation in and through the ionosphere, which depends intimately upon the effect of the Earth's magnetic field and the whistler mode of propagation. Although there may be important, if specialized, communication aspects of this mode, it is of particular interest to ionospheric physicists in studying by the aid of satellites the upper regions of the ionosphere extending into the magnetosphere.

## 5 Cooperation with URSI

The above reference to ionospheric physicists illustrates the reference made in the Introduction to URSI. Indeed there is an overlap between the interests of URSI and CCIR over almost the whole range of Study Groups 5 and 6 of CCIR. For instance, URSI has Commissions on both tropospheric and ionospheric matters, and there is cooperation between them and Study Groups 5 and 6 respectively. It is natural that this should mainly take the form of requests from the CCIR to URSI for information on scientific matters that may affect the use of radio for communications, but the standard procedure is to add a footnote to a document drawing the attention of URSI to the matter under discussion and to invite comment on it.

In recent years Study Group 6 has made its requests to URSI more specific, and URSI has made a very useful response in documents that have been submitted at the Interim and Final Meetings, and have formed the basis of Study Group 6 Reports. Radio has played a major part in elucidating the structure of the ionosphere by means of ionograms of equivalent height as a function of frequency, taken at vertical and oblique incidence with both ground-based and top-side sounders. In return the study of the structure, and in particular the irregularities of the ionosphere has revealed the mechanisms of ionospheric propagation, showing for instance the effect of sporadic E and of tilted layers on the maximum usable frequency for a given circuit at any particular time.

Perhaps the phenomenon of magneto-ionic double refraction, especially at the lower frequencies, has led to the most remarkable advances in our knowledge of the ionosphere and the magnetosphere, and the complex mechanism of solar winds by which charged particles from the Sun enter the ionosphere under the combined action of the magnetic fields of the Sun and the Earth.

## 6 Conclusion

In this review of the work of the CCIR in the field of ionospheric propagation no attempt has been made to go into great detail. The chief aim has been to draw the attention of the radio engineer to the fund of information that exists in the documents of the CCIR. While this information is directed in the first instance to the parent body, the ITU, with special reference to the needs of the IFRB, it provides an invaluable guide to those engaged in the application of radio to communications, where a knowledge of propagation characteristics is vital to the implementation of the radio systems dealt with in the other Volumes of the CCIR Documents.

For the reasons stated, the descriptions have referred to the New Delhi 1970 Documents and, with special exceptions, the Document numbers of the various Reports etc. have not been given, but indications are given of some of the proposed revisions that are to be presented for adoption at the Geneva 1974 Plenary Assembly.

*Manuscript received by the Institution on 22nd July 1974 (Paper No.1622/Com. 103).*



## *The Author*

**Mr. George Millington** took the Natural Sciences Tripos while at Clare College, Cambridge, and he subsequently graduated in physics both at Cambridge and London in 1926. He did two years research at the Cavendish Laboratory before going to the Columbia Graphophone Company where he carried out acoustical research. In 1931 he joined the Research Department of Marconi's Wireless Telegraph Company to work on radio propagation under T. L. Eckersley. During the second world war he was a member of the Inter-Service Ionosphere Bureau at the Marconi Research Laboratories at Great Baddow. On Mr. Eckersley's retirement in 1946 he was made Chief of a Propagation Theory Group and became involved in the work of the CCIR. He attended the ITU Conference at Atlantic City in 1947 and subsequently became the Leader of the United Kingdom delegates at the meetings of Study Group 6 of the CCIR on ionospheric propagation. He was a Senior Consultant for some years before his retirement from the Marconi Company in 1970, and he was then invited to be a part-time Consultant at the Ministry of Posts and Telecommunications to continue his responsibilities at the CCIR until the Final Meetings of Study Group 5 and 6 at Geneva in February 1974. During his career he has published many papers and he was awarded the Faraday Medal of the Institution of Electrical Engineers in March 1974 'for his distinguished theoretical studies in radio propagation'.

UDC 551.510.5.029.45: 621.336.9

# The propagation of l.f. and v.l.f. radio waves with reference to some systems applications

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SUMMARY

An outline is presented of the theoretical methods available for determining the propagation characteristics of v.l.f. and l.f. waves for both long and short transmission paths. Attention is drawn to the differences between the ray-hop and wave guide mode theories which have been applied to these frequency bands.

The experimental study of v.l.f./l.f. propagation is discussed and the variations in the phase and amplitude of the received signals during normal and disturbed conditions are described. A comparison is made between the experimental results and those predicted from theoretical considerations. Some examples are given of the application of v.l.f./l.f. waves to navigation (mainly *Omega*) and to communications.

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## 1 Introduction

The propagation of low and very low frequency radio waves has been of considerable practical importance and interest from the earliest days of radio. The epoch-making experiments of Marconi at the beginning of the century, which showed the possibility of intercontinental radio communications, were carried out using radio waves in what we now call the low frequency band. These experiments gave great impetus to the development of long and very long wave radio communications and to studies of their propagation characteristics, especially to the variation of signal strength with distance from the transmitter.

It was soon apparent that v.l.f. and l.f. radio waves were reflected from the lowest part of the ionosphere and extensive studies of the reflecting medium were undertaken in the late 1930s by the group at Cambridge, England. The investigations showed that, apart from sunrise and sunset periods, the reflecting region was remarkably stable. Thus the propagation of v.l.f./l.f. waves was, in general, characterized by high stability in both phase and amplitude. Furthermore, little attenuation of the waves occurred in the ionospheric reflexion process, and as a result, they could be propagated to very great distances as had been demonstrated earlier by Marconi.

The great disadvantages of v.l.f./l.f. communications were the limited bandwidth available and the high cost and low efficiency of the transmitting installations. The development of short wave radio in the 1920s was possible because these disadvantages did not exist and interest in low frequency propagation waned. In the last 20 years interest in these long waves has revived, due primarily to their use in navigational aids. The inherent phase stability of this type of propagation is an essential feature of a world-wide navigation system. The development of high stability oscillators has, in addition, allowed these transmissions to be used for world-wide frequency and time comparisons. One important property of very low frequency radio waves which has recently been exploited, is their relatively deep penetration into the earth. Sub-surface communications have been shown to be possible; these waves have also been used for geological prospecting and in mine rescue.

The object of this paper is to review the progress made in the experimental and theoretical study of v.l.f./l.f. waves and to describe a few applications of this type of propagation in the fields of communications and navigation.

## 2 Theoretical Determination of Propagation Parameters

The ability to determine theoretically the variation of the reflexion parameters of v.l.f./l.f. waves as a function of frequency and distance is of considerable advantage in the design of navigation and communications systems utilizing these frequencies. Such calculations enable propagation information to be obtained in areas where experimental observations are lacking and enable the various system parameters to be optimized for any given circuit. A comparison of the calculated propagation

parameters with those measured experimentally enables information to be obtained regarding the validity of the electron density and collision frequency distributions assumed in the calculations. A knowledge of these distributions is important since they form the starting point for calculating the reflexion parameters and are also essential for the study of the physical processes which occur in the lower ionosphere.

A number of semi-empirical techniques for calculating the phase and amplitude of v.l.f./l.f. waves propagated to medium distances have been developed by Volland[1] and Frisius.[2,3] Approximate values are obtained without recourse to rigorous mathematical treatment. With the advent of large high-speed computers exact solutions of the appropriate magneto-ionic equations have become possible and such methods are now in common use to determine exact values of the reflexion parameters of any given ionospheric model in the v.l.f. and l.f. bands.

At low and especially at very low frequencies the medium through which the wave propagates can vary appreciably in the space of one wavelength. Thus, the conventional ray optics used to describe the propagation of high frequency radio waves in the ionosphere no longer applies. Full-wave solutions become necessary in which the wave fields are calculated at many points in the course of one wavelength. A number of full wave methods have been developed for calculating the reflexion properties of the lower ionosphere at low and very low frequencies.

When propagation takes place to great distances further complications occur in that a large number of ray paths can be established between the transmitter and receiver. This can conveniently be represented in terms of waveguide mode propagation, where the Earth and the ionosphere form the walls of a spherical waveguide. A combination of full wave and waveguide mode analysis enable the phase, amplitude and polarization of v.l.f. and l.f. waves propagated to great distances to be determined for any type of ionospheric model and propagation path.

## 2.1 Full-wave Methods

The differential wave equations governing the propagation of radio waves in the ionosphere are linear and homogeneous, thus the sum of any solution is itself a solution. In the usual methods of calculation[4] the differential equations satisfying some field component of the wave are first formulated. Solutions are then obtained at great heights, well above the reflexion levels, and these correspond to purely upgoing waves. Connexion formulae are applied to obtain solutions down through the ionosphere. Below the ionosphere these are separated out into upgoing and downgoing waves. From these the reflexion coefficients are calculated, which will depend on the polarization of the incident wave. In general, the incident and reflected waves do not have the same polarization and the reflexion properties must be completely specified by the four parameters ${}_{\parallel}R_{\parallel}$, ${}_{\parallel}R_{\perp}$, ${}_{\perp}R_{\perp}$, ${}_{\perp}R_{\parallel}$.

Numerical methods for full wave solution of the wave equations have been extensively discussed in the literature.[5-9] These methods differ in detail but to illustrate the procedure the Pitteway solution[8] is outlined since this has been extensively used by many groups of workers.

The equation of motion of a single electron in the wave field may be written[10] as

$$P = \varepsilon_0 \mathbf{M} E \qquad (1)$$

where the susceptibility tensor $\mathbf{M}$ is given by

$$\mathbf{M} = -X \begin{pmatrix} U & \mathrm{j}Y_z & -\mathrm{j}Y_y \\ -\mathrm{j}Y_z & U & \mathrm{j}Y_x \\ \mathrm{j}Y_y & -\mathrm{j}Y_x & U \end{pmatrix}^{-1} . \qquad (2)$$

The conventional notation of the magneto-ionic theory[4] is used throughout.

Following Pitteway the coordinate axes are defined by the Earth's field, and are chosen so that $Y_x$ vanishes. $Y$ is assumed constant at all heights.

The four wave-field equations can be written in matrix form

$$e' = -\mathrm{j}kTe \qquad (3)$$

where $e$ is the column vector

$$e = \begin{vmatrix} E_x \\ -E_y \\ H_x \\ H_y \end{vmatrix}$$

and T is a $4 \times 4$ matrix.

$$T = \begin{pmatrix} -\mathrm{j}lB_1 & lB_2 & lmB_3 & 1-l^2B_3 \\ \mathrm{j}mB_1 & -mB_2 & 1-m^2B_3 & lmB_3 \\ -lm+\mathrm{j}B_4 & 1-l^2-B_5+XY_y^2/\alpha & -mB_2 & lB_2 \\ 1-m^2-B_5 & -lm-\mathrm{j}B_4 & -\mathrm{j}mB_1 & \mathrm{j}lB_1 \end{pmatrix}$$

where

$$B_1 = XUY_y/\alpha$$
$$B_2 = XY_yY_z/\alpha$$
$$B_3 = U(U^2-Y^2)/\alpha = 1+X(U^2-Y_z^2)/\alpha$$
$$B_4 = XY_z(U-X)/\alpha$$
$$B_5 = XU(U-X)/\alpha \qquad \alpha = U(U^2-Y^2)-X(U^2-Y_z^2)$$

The incident wave normal has direction cosines $l$, $m$ $n$ and the functional dependence comes through the variation of $X$ and $U$ with height.

The four linear differential equations (3) are integrated numerically. The computer forms derivatives of (3) at the starting values (at great heights) and uses these to calculate the wave fields at a slightly lower height. Fourth-degree polynomials are used to fit the solutions of the differential equations by calculating four separate sets of derivatives at each height. The process is then repeated towards the bottom of the ionosphere until free space is reached. Here the solution is separated into upgoing and downgoing components and the reflexion and conversion coefficients determined.

Care must be taken during the numerical integration to ensure that the two solutions remain independent. Suitable constraints are applied to the solutions at each integration step so that the second solution is not swamped by the dominant solution. Full details of these techniques are given by Pitteway.[8]

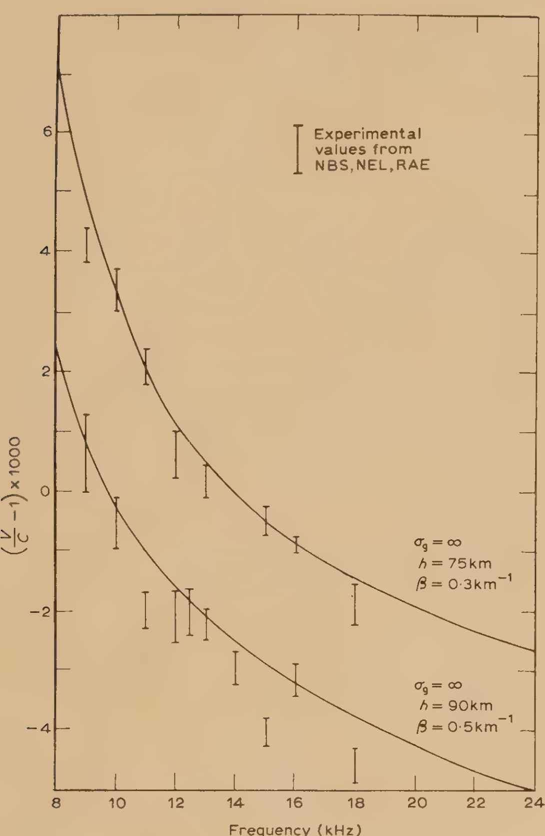



**Fig. 1.** Comparison of calculated and measured values of the phase velocity parameter (after Wait and Spies, 1964[19]).

A somewhat different approach to full-wave calculations has been proposed by Altman[12] and Altman and Cory.[11] Here the Pitteway method is modified to give 'full-wave' ordinary and extraordinary transfer coefficients for slabs of the ionosphere of various thickness. The ratio of the transmitted or reflected energy flux to the incident value is then calculated for each slab. This full-wave slab approach proved time-consuming since each slab requires a separate numerical integration and little information can be stored for subsequent calculations. To overcome this drawback a generalized thin-film optical analysis was developed by Altman and Cory.[11,13] The ionosphere is divided into a large number of thin layers and $2\times 2$ transfer matrices calculated at each layer interface. Multiple reflexion within each elementary layer generates a geometric series of matrices which when summed, yield overall $2\times 2$ transfer coefficient matrices of the layer. An iterative procedure repeats the process layer after layer so that the thickness of the resulting slab increases progressively downwards giving the overall reflexion and transmission coefficient matrix of the total ionospheric region in terms of the characteristic magneto-ionic modes.

Various other types of numerical full-wave analysis have been developed, e.g. Inoue and Horowitz[9] and Johler and Harper.[14] They all enable the complex reflexion and conversion coefficients to be determined for any given height distribution of electron density and collision frequency. Parameters such as the wave frequency, path azimuth, angle of incidence, and geomagnetic field intensity are easily varied. Thus the reflexion parameters of v.l.f. and l.f. waves can be calculated for conditions representative of any time of day, season and geographical location. Clearly this technique provides a powerful tool in the design and operation of any v.l.f./l.f. radio wave system.

## 2.2 Waveguide Mode Propagation

The theory of v.l.f. radio wave propagation in the terrestrial waveguide has been extensively developed by Budden[15], Wait[16], Galejs[11] and Pappert.[18]

At these frequencies for long range propagation, the Earth behaves like a good electrical conductor with a reflexion coefficient approaching +1 while the ionosphere has a reflexion coefficient approaching −1. It is convenient thus to treat the Earth and the ionosphere as the two boundaries of a spherical waveguide and to consider propagation to great distances in terms of waveguide modes.

A vertical electric antenna situated on the surface of the Earth will excite transverse magnetic waveguide modes (TM modes). For each mode there are three parameters which govern the characteristics of the mode, i.e. the attenuation rate, in dB|Mm; the phase velocity of the mode, usually quoted relative to the velocity of light, $v/c$; and the excitation factor $\Lambda$, which is approximately the ratio of the power launched into the Earth ionosphere waveguide to that launched into a flat waveguide with perfectly conducting boundaries. To indicate how these parameters vary with frequency, Figs. 1, 2 and 3 show theoretically derived values by Wait and Spies[19] of $v/c$, attenuation and $\Lambda$ for modes 1 and 2, for a representative model of the ionosphere boundary for both daytime and night-time with the lower boundary of the waveguide being sea water (effectively a perfect electrical conductor of conductivity, $\sigma_g$=infinity). In these curves the ionospheric boundary is represented by a conductivity parameter $\omega_r$ which varies in an exponential manner with height:

$$\omega_r = (\omega_r)_0 \exp \beta(Z - Z_0)$$

$Z$ is a measure of distance above a reference level $Z_0$ where the conductivity parameter has a value $(\omega_r)_0$ and $\beta$ is a constant. The values of $\beta$ suggested by Wait and Spies[19] to represent the day and night profiles of the conductivity of the lower ionosphere are 0·3/km and 0·5/km respectively.

From these curves a number of general features are immediately discernible which experimental results can test. Mode 2 suffers a larger attenuation than mode 1 and this difference is more marked for the lower frequencies. Also, the difference in the phase velocity between night and day conditions of mode 1 is larger at the lower than at the higher frequencies. This indicates that at large distances from a transmitter where mode 1 would be the dominant mode both by day and night the diurnal phase delay pattern should (1) increase in magnitude linearly with distance and (2) have a larger magnitude the lower the frequency. Both these indications are borne

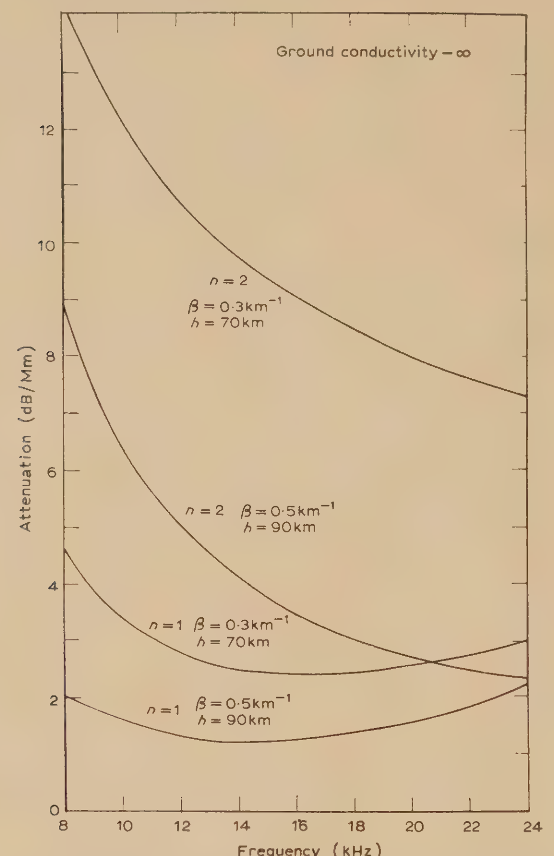



**Fig. 2.** Calculated attenuation rates for the first and second TM modes as a function of frequency (after Wait and Spies, 1964[19]).

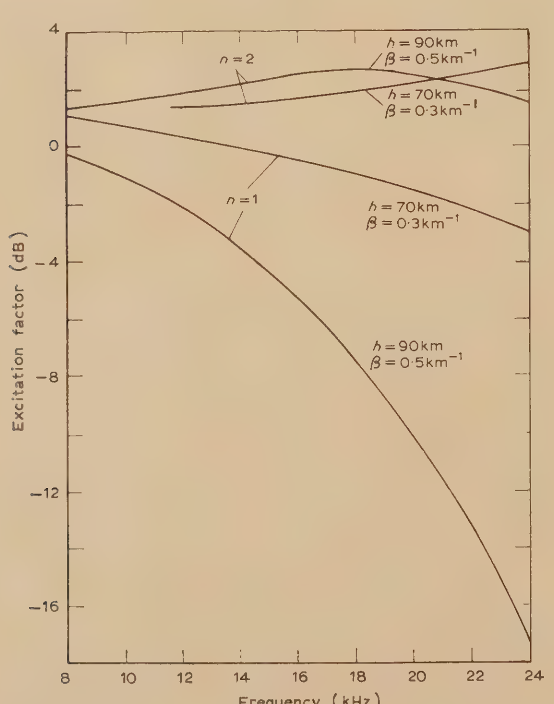



**Fig. 3.** Calculated excitation factors for day and night conditions (Wait and Spies, 1964[19]).

out by the experimental results. For distances closer to a transmitter the effects of the second mode should become more marked. This is especially so at the higher frequencies since at these frequencies, as may be seen from Fig. 3, the second mode is more easily excited in the waveguide; at 20 kHz, for example, the excitation factor for mode 2 is some 10–15 dB greater than for mode 1 under night conditions while at 10 kHz they are more or less equally excited. Figure 4 shows a theoretical estimate of the diurnal phase delay variation at 16 kHz based upon the waveguide model stated above, where the reference heights for day and night are 75 and 88 km respectively. This theoretical curve shows the effect of the second mode in the departure of the curve from a linear form. Of special interest is the manner in which the theoretical curve fits the experimental data for distances in the 1000–3000 km range. A corresponding curve for 10 kHz is also shown, from which it is evident that the effect of the second mode is much smaller, due to (1) its larger attenuation rate under day conditions and (2) the larger excitation factor of mode 1 at this frequency compared to 16 kHz.

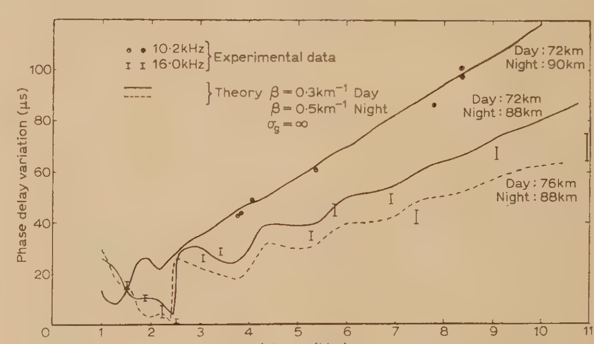



**Fig. 4.** Magnitude of diurnal phase delay variation versus distance for 10·2 kHz and 16 kHz.

Further more detailed characteristics of v.l.f. propagation are given in Section 3 of this paper.

The general characteristics of v.l.f. propagation as outlined above have been derived from the theoretical approach pioneered by Wait[16] and Budden[15] and verified by experimental measurements. The theory was limited to the simple models of the ionospheric boundary and experimental measurements, undertaken in connexion with navigational aid development, indicated areas where theory could not account for measured data. Theoretical advances by Galejs[17] and Pappert[18] enabled an arbitrary ionospheric profile together with an arbitrary terrestrial magnetic field to be incorporated in the waveguide model. These, together with an appropriate choice of a lower ionosphere model, have allowed much better correlation between theory and experiment (Galejs,[17] Foley, Wand and Jones,[20] Bain and Harrison.[21])

### 2.3 L.F. Propagation

The waveguide mode theory of propagation is useful when one is restricted to considering not more than say a few modes. This holds for frequencies less than about 30 kHz. At higher frequencies it is more appropriate

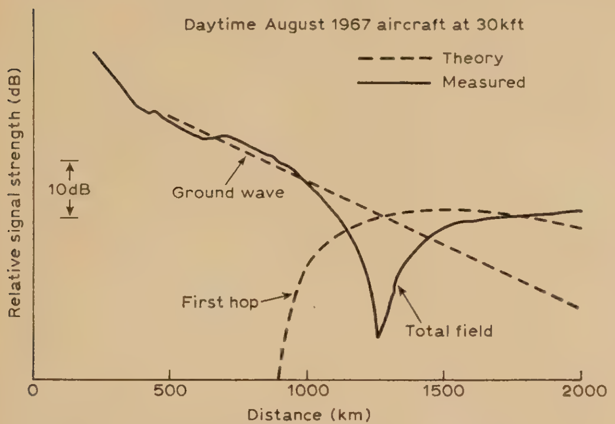



**Fig. 5.** Comparison of calculated and measured signal strength at 60 kHz as a function of distance from transmitter (MSF).

to view propagation in terms of wave-hops (Berry and Chrisman[22]), though Johler[23] has developed a theory covering the frequency range from v.l.f. to m.f. which considers propagation in terms of spherical wave functions.

In the wave-hop theory, the full-wave solution for propagation between a spherical Earth and a concentric ionosphere can be expanded into a series of complex integrals. If these integrals are replaced by their saddle-point approximations the series can be identified as the ray hop series of geometric optics, and thus these integrals are called wave-hops. The saddle point approximation is inadequate near and beyond the caustic and in this area the wave-hops can be evaluated by numerical integration or by summing a residue series. Berry and Chrisman[22] represent the series in the form

$$E = E_0 + \sum_{j=1} R_j I_j$$

where $E_0$ is the groundwave and $R_j$ is the ionospheric reflexion coefficient as discussed earlier in this paper. The path integral $I_j$ takes into account ground conductivity, path length, reflexion height and earth curvature.

Figure 5 illustrates the use of this theory in computing the signal strength as a function of distance for a frequency of 60 kHz and an appropriate ionospheric model. Also shown is an experimental plot of signal level against distance as measured in an aircraft flight over the MSF transmitter (Rugby) in a northerly direction. The agreement is good. Up to the present the validation of the theory has been limited by the restricted amount of experimental data available.

## 3 Propagation Characteristics of V.L.F./L.F. Radio Waves

Attention is now given to the experimental investigation of the propagation of v.l.f. and l.f. waves via the ionosphere. The early work of Marconi has already been referred to and following his successful transatlantic transmissions in 1901, rapid developments were made in developing the l.f. band for communication purposes. The early experiments soon showed that the signal strength varied with time of day, and marked differences were noted in the signal strength received during day time and at night. However, it was not until the work of Appleton and Barnett in the mid-1920s that these changes were conclusively associated with changes in the reflecting layer. Much larger signals were received at night at all frequencies although deep fading did occur. Day-time conditions were found to be more stable however, and choice of frequency was important as there was evidence suggesting that the signal strength increased with decreasing frequency. The transition from day to night and vice-versa was not a smooth one and the signal strength passed through more than one maximum and minimum value.

In the presence of a reflecting layer, interference might be expected between the direct ground wave and the reflected signal. Hollingsworth,[24] using a frequency of 21·4 kHz, demonstrated the interference as a series of well-defined maxima and minima of signal strength with increasing distance from the transmitter. From these observations he deduced an equivalent height of 75 km for the reflecting layer for summer midday conditions. Propagation anomalies associated with solar and magnetic disturbances were soon noted as indicated by Espenschied, Anderson and Bailey[25] and Austin.[26] The influence of the earth's magnetic field was appreciated at this early stage and Round *et al.*[27] noted that propagation from East to West was more difficult than from North to South.

In the 1930s the use of v.l.f./l.f. radio waves for communication purposes declined; however, there was great interest in developing low frequency techniques for studying the lower ionosphere. A considerable amount of research on this subject was undertaken at the Cavendish Laboratory, Cambridge in the years up to 1955. These investigations provided a detailed understanding of the behaviour of the lower ionosphere and established the propagation characteristics of these waves out to distances of about 1000 km from the transmitter. The characteristics of the wave propagation that were studied during this period were the 'apparent height' of reflexion of the waves its amplitude and polarization after reflexion at oblique and vertical incidence, the diurnal and seasonal variations of the reflexion height and the effects of sudden ionospheric disturbances and magnetic storms.

### 3.1 Undisturbed Conditions

One of the techniques developed by the Cambridge group was that of comparing the phase of the downcoming sky wave with that of the direct ground wave. This interferometer technique enabled accurate measurements of the changes in the apparent height of the reflecting layer.[28] A typical example of these results is reproduced in Fig. 6,[29] and shows changes of phase with time of day of the 16 kHz sky wave received at a distance of 90 km from the transmitter. The phase changes behave in a very regular manner and if there is no phase change on reflexion then the phase variations correspond to the variations of the reflection height of the lower ionosphere. During the day this behaviour is very regular and shows a weak solar zenith angle dependance

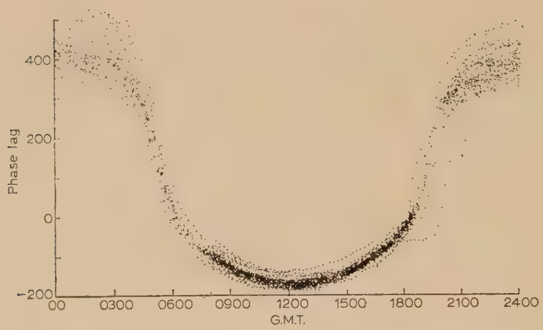



**Fig. 6.** Change of phase of skywave (16 kHz) with time of day (after Bracewell *et al.*, 1951[29]).

which can be represented as

$$h = h_0 + A(t) \log_e (\sec \chi)$$

$h$ and $h_0$ are the apparent heights of reflexion when the Sun's zenith angle is $\chi$ and zero degrees respectively. $A(t)$ is a constant for any given day.

The change in apparent height from day to night at 16 kHz was found to be 17 and 13 km for summer and winter conditions respectively. On frequencies near 100 kHz the change during the day-night transition in winter is about 7 km, while in summer the absorption of the signals is so large that no measurements could be made.

In addition to these steep incidence observations, measurements were made to distances of up to 1000 km. Up to 500 km, the 16 kHz observations were very similar to the steep incidence results; however, beyond this range, the phase of the signal starts to advance about 1 hour before sunrise and remains fairly constant during the day showing very little zenith angle dependance. These results have been interpreted in terms of two reflecting layers in the D region, where the lower layer reflects the waves at distances of 500 km or more. The behaviour of the two layers is different and thus suggests that they are formed by different mechanisms. Similar results were obtained using higher frequencies.

Detailed investigations of the propagation of l.f. waves to distances of up to 1000 km have been undertaken by the group at Kuhlungsborn, East Germany. These experiments indicated that the behaviour of radio waves in the 100 to 700 kHz band can be quite different to that at lower frequencies.[30,31] Marked fading effects were observed at night and these propagation paths were also sensitive to transient disturbances in the D region.[32,33] A review of these experiments has been given by Lauter.[34]

Studies of v.l.f./l.f. wave propagation at high latitudes have been made by Belrose and co-workers and very large disturbances are noted during geomagnetic storms.[35] At very high latitudes the diurnal phase and amplitude variations are considerably modified since some part of the propagation path remains entirely sunlit or in darkness for long periods. Many of these unusual features have been commented on by Belrose.[36]

The variation of signal strength as a function of distance from the transmitter was studied by Budden, Ratcliffe and Weekes[37] using a technique similar to that of Hollingsworth.[24] After the war this work was continued by Weekes,[38] Williams,[39] and Weekes and Stuart.[40] A series of maxima and minima were obtained in the signal strength as a function of distance from the transmitter as shown in Fig. 7.[29] These results were similar to the original observations of Hollingsworth and could be explained in terms of simple D region models for distances up to about 400–500 km from the transmitter. Beyond 500 km the same model could not account for the measurements and a two layer profile seemed necessary.

In all these experiments the absorption of the l.f. waves was found to be considerably greater than for the v.l.f. waves. Bracewell *et al.*[29] studied the frequency dependance of the reflexion coefficients. Below 20 kHz, the variation from night to day is from a coefficient of 0·50 to about 0·10 in summer, whereas, at 100 kHz for the same conditions, it varies from 0·20 to a value less than 0·0001. During winter day time the medium is a much better reflector giving reflexion coefficients of 0·35 (<20 kHz) and 0·03 (~100 kHz). As the path becomes more oblique the reflexion coefficient increases to a maximum at grazing incidence.

Early investigations of the propagation of v.l.f. waves to great distances were confined to measurements of amplitude only.[41,43] It was not possible to study the phase of the signals since the ground wave cannot be used as a reference at great distances and the oscillators then available were not sufficiently stable to allow a locally-generated reference. In the early 1950s very stable crystal oscillators were developed and soon afterwards atomic frequency standards became available as normal laboratory equipment. The availability of stable oscillators and the growing interest in v.l.f. navigation prompted several investigations of the long distance propagation of these waves.[44,46] The very marked changes which occur in the diurnal pattern of phase variation has been summarized by Belrose[46] and is reproduced in Fig. 8. It is evident from the Figure that the greatest phase changes occur at sunrise and sunset

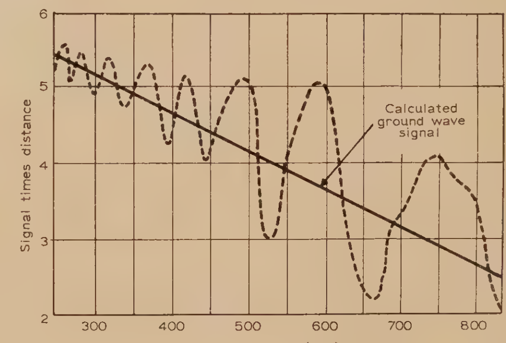



**Fig. 7.** Variation of signal strength as a function of distance from an 85 kHz transmitter (after Bracewell *et al.*, 1951[29]).

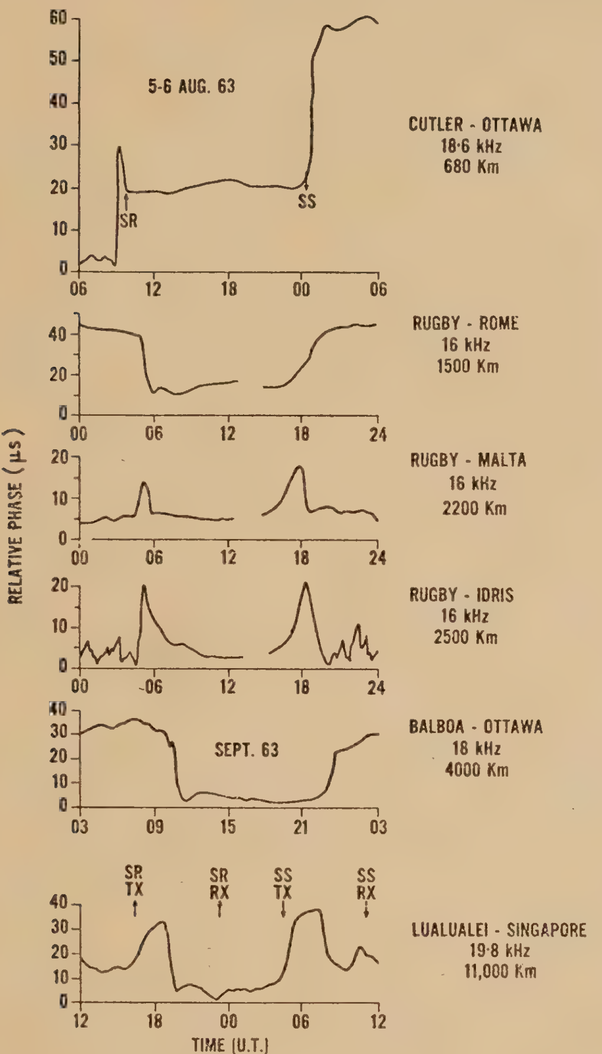



**Fig. 8.** Diurnal variations in the phase of v.l.f. signals propagated over paths of various lengths (after Belrose, 1968[36]).

and these phase transitions have been extensively studied.[47–50] In general the sunrise/sunset behaviour has been explained in terms of waveguide modes converted by the sunrise/sunset discontinuity in the ionospheric boundary of the Earth-ionosphere waveguide interfering with those which propagate through the discontinuity unmodified, as outlined by Crombie.[48,51] Some observations show additional complicating features as indicated by Chilton *et al.*[52]

The propagation of v.l.f. waves over high latitude paths exhibits some novel features since the diurnal changes are produced when only part of the path is illuminated. Some interesting mode structure can occur in these cases.[53, 54]

### 3.2 Disturbed Conditions

The discussion, so far, has been concerned with the normal diurnal changes observed in the propagation characteristics. The lower ionosphere is however sensitive to a number of geophysical disturbances, such as those resulting from solar flare and magnetic storm activity. During flare conditions the solar x-ray flux is enhanced and additional ionization is produced in the D region. The effective reflexion height is decreased and a phase advance is noted on short propagation paths.[38,55,56] On certain long propagation paths a phase retardation is noted during flare activity and can be explained by waveguide mode interference.[57] In addition to the phase anomalies, the amplitude of the signal is also affected. The exact form of the amplitude change can be quite complex and depends on both the path and the frequency.

In contrast to the short period disturbances induced by the flare enhancement of solar x-rays a number of long duration disturbances are also observed.

On high latitude paths (>60°) phase and amplitude anomalies are observed during solar cosmic ray events. The cause of these events, which last for several days, is enhanced ionization of the D region by solar protons in the energy range 80–100 MeV which are emitted during solar flares. In general this produces a lowering of the reflexion heights of the v.l.f. and l.f. waves and a corresponding change in the received phase. The night-time phase is depressed and the diurnal phase variation can disappear entirely. The night-time amplitude is less than normal but during the day the signal level is normal or even increased. These effects are dependent on the latitude of the propagation path and have been discussed in detail by Lange-Hesse and Rinnert,[58] Ortner *et al.*,[59] and Belrose and Ross.[35]

Perhaps the best known disturbance effects on v.l.f./l.f. propagation are those associated with geomagnetic storms. During magnetic storms, anomalies are produced in both the phase and amplitude of v.l.f. and l.f. waves propagated over both short and long paths. These events are of long duration, lasting for up to ten days or more. The main features associated with the storm activities at l.f. have been summarized by Lauter and Sprenger[32] and Lauter and Knuth.[33] These authors note that the sudden commencement of the geomagnetic storm does not affect the received signal strength. The main phase of the storm produces deep fading at night and this is known as the primary storm effect. No daytime anomalies are noted during the main phase of the storm. For large storms high absorption sets in 3 or 4 days after storm commencement and continues for several days; this is the so-called storm after-effect. Similar behaviour has been noted on v.l.f. signals propagated at steep incidence.[46] The phase of the v.l.f. signals is sensitive to storm effects and phase advances are noted, particularly at night, as shown in Fig. 9. For long-path v.l.f. propagation both the night and day-time phase is advanced and the regular day/night transition is displaced. Finally anomalies in the phase and amplitude of v.l.f. and l.f. propagation have been reported which are related to changes in the temperature at stratospheric heights (i.e. 1 mb pressure level). The phase of both l.f. and v.l.f. signals are found to be advanced during some periods in winter when anomalies in the D region electron density exist. These winter anomalies, first noted as increases in the absorption of

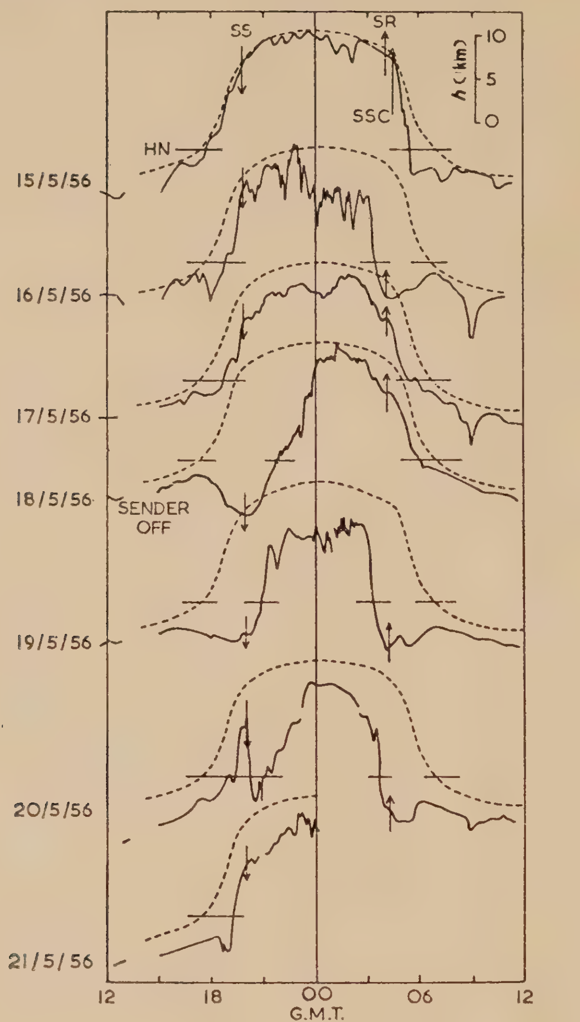



**Fig. 9.** Diurnal phase changes during and after a geomagnetic storm (after Belrose, 1968[36]).

high-frequency radio waves are related to stratospheric warmings, and deviations from the normal v.l.f. and l.f. diurnal patterns have been noted during these events.

Propagation anomalies are also produced by meteor showers, nuclear detonations and during solar eclipse (Buckmaster, 1968).[60] These are transient disturbances and their magnitudes are normally less than the normal diurnal changes. For this reason they are not considered to be major disruptive factors in practical v.l.f./l.f. propagation systems.

The studies of v.l.f. and l.f. waves described above were directed at a better understanding of how these waves propagate, and to interpret the propagation data in terms of the physical processes which govern the behaviour of the reflecting region. These basic studies were an essential prelude to the development of modern navigation and communications systems in these wave bands. The next Section contains details of some of these systems and indicates how the highly stable nature of v.l.f. propagation has been employed.

## 4 Applications of V.L.F./L.F. Propagation

When dealing with communication or navigational radio systems in the v.l.f. to l.f. bands, which operate over distances of 1000 km or more, the influence of the ionosphere on the propagation of the radio waves, which carry the information necessary for communication or navigation, becomes very marked. While it is true that this type of long range circuit can operate only because the ionosphere exists, the variability of the ionosphere is the major cause of the unreliability of such systems.

In the case of long-range radio navigational aids, it is usually the relative phase of transmitted signals that is of prime importance and it is the prevailing ionospheric conditions, which govern the variability of the phase delay of the transmitted signals, that ultimately define the accuracy and reliability of such systems. Radio aids to navigation such as *Decca* (70–130 kHz) and *Loran C* (100 kHz) give remarkable accuracy while the received signals are within ground wave propagation range. When ionospheric propagation starts to make a contribution to the received signal the accuracy of the system deteriorates markedly.

Very low frequency radio waves (3–30 kHz) have the property that they can propagate on a world-wide basis with small attenuation rates of order 2 to 3 dB/Mm. Further, they have the property that the phase delay suffered by signals propagating over a given large distance follows a predictable diurnal pattern. When used in a navigation technique this property allows an inherent accuracy of approximately 1 to 2 km. However, it is still the variability of the ionosphere which governs the ultimate accuracy of navigational aids using v.l.f. radio waves. In this context, because the ionosphere is known to be more liable to disturbing influences at high latitudes than at lower latitudes, the use of such aids will probably be accompanied by a degradation in performance in these regions, and this degradation will have to be ascertained.

### 4.1 *Omega* Navigational Aid

At present there seems likely to be only one proposed v.l.f. navigational aid that will become operational; that is the US Navy's *Omega* system. Already four transmitters, out of eight planned, are radiating part of the

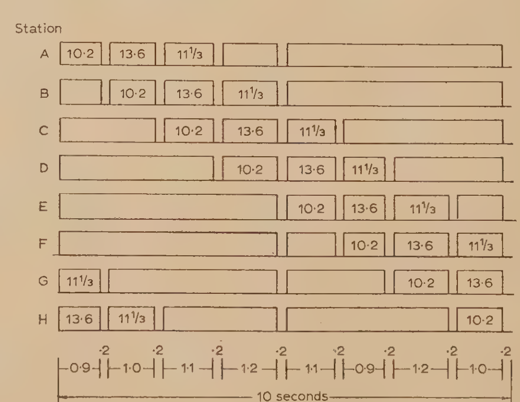



**Fig. 10.** *Omega* transmission format.

frequency-time multiplex transmissions. This is allowing an evaluation of the aid to be performed under varying ionospheric conditions.

*Omega* is a world-wide navigational aid,[61] using frequencies in the 10–14 kHz band, at present being developed and implemented by the US Navy. A pair of transmitting stations provides the navigator with a family of hyperbolic lines-of-position (l.o.p.), and eight transmitting stations with 5000–6000 km baselines will give a global coverage. The eight transmitters, named A, B, C . . . H, will radiate the frequency format shown in Fig. 10. All transmitters will be phase-synchronized and repeat their individual radiated format every 10 seconds, the 10 second period beginning at 00 00 hour and synchronized to UT2.

The 10·2, 11⅓ and 13·6 kHz transmissions are the basic navigation frequencies; other radiated frequencies, unique to each transmitter, may be used for navigation by distance measurement based on a cycle counting technique.

The *Omega* frequency of 10·2 kHz is accepted as the basic frequency for navigation and charts depicting *Omega* l.o.p.s for a frequency of 10·2 kHz are presently available for certain areas of the world. These 10·2 kHz l.o.p.s have ambiguities spaced by 15 km on the baseline joining two transmitters and for marine use, where the vessel is slow moving, the resolution of these 15 km ambiguities can be achieved by dead reckoning means. However, if necessary, the 13·6 kHz transmissions could be utilized in conjunction with the 10·2 kHz transmissions to give ambiguous l.o.p.s separated by some 45 km on the baseline.

The exact positions of these l.o.p.s on a chart, relative to known geographic coordinates, are governed by the value of the propagation velocity, $v$, that is used for the appropriate frequency. For 10·2 kHz, the standard value used is given by $c/v = 0{\cdot}9974$ where $c$ is the velocity of propagation in free space (299 792·5 km/s).

The questions which are then posed are that, since the velocity of propagation is a function of many geophysical parameters such as ground conductivity, direction of propagation, effective height of ionospheric reflexion, how do the l.o.p.s vary about the charted values, temporally and spatially; can one correct for these variations; what is the final accuracy of the system; what is the magnitude and duration of the largest errors one is likely to experience?

## 4.2 Propagation Aspects in *Omega*

For frequencies appropriate to *Omega* the broad features of the propagation characteristics may be explicitly stated. Only two modes, namely modes 1 and 2, are of importance in the context of *Omega*, and over the frequency band covered, 10–14 kHz, mode 2 is excited more than mode 1 by some 1–4 dB. Further, mode 2 is propagated with a higher phase velocity than mode 1 and hence as the modes travel away from a transmitter they will move in and out of phase with one another, causing an interference effect which will be apparent in the magnitude of the resultant field strength. Figure 11 depicts such an interference effect, measured on board a high speed aircraft, appropriate to the 10·2 kHz transmission from *Omega* Trinidad under night conditions.

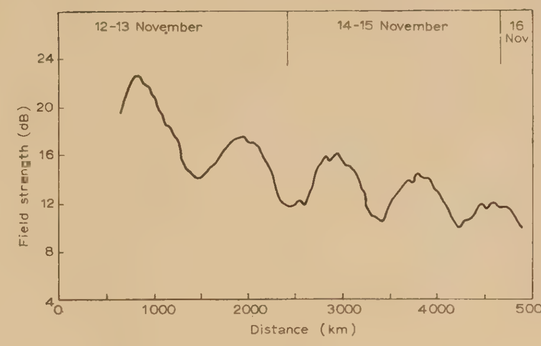



**Fig. 11.** Variation of 10·2 kHz field strength as a function of distance from the *Omega* Trinidad transmitter.

### 4.2.1 *Optimum frequencies for navigation*

From the experimental and theoretical considerations of v.l.f. propagation discussed earlier, the lower frequency band of 10–14 kHz has definite advantages over the higher frequencies for navigational purposes. The main advantage is that due to the frequency dependence of the attenuation and excitation factors of the modes, the second mode perturbing effects are much smaller in this lower frequency band.

At frequencies below 10 kHz the attenuation rates increase rapidly to high values. This, coupled with the economics of designing efficient ground transmitting aerials at this end of the band, effectively puts a lower limit of about 8 kHz to the optimum band for navigation use.[61]

These considerations together with the maxim of using as low a frequency as possible for lane resolution has led to the *Omega* World-Wide Navigational System choosing its main frequency of transmission as 10·2 kHz.

### 4.2.2 *Stability of propagation*

Of particular importance to navigational purposes is the overall stability of propagation. This is best demonstrated by considering the long-term monitoring of a l.o.p. at fixed sites. Figure 12 illustrates the monthly mean value and its variability (standard deviation) for the two l.o.p.s (B–A) and (D–B) derived from the 10·2 kHz transmissions from *Omega* Trinidad (B), *Omega* Norway (A) and *Omega* New York (D). It is evident that (1) the standard deviation of l.o.p.s is small, being of order 5 cels (1 cel is 1/100th of a lanewidth) and (2) there is a very marked dependence of the l.o.p. reading on time of day. Similar values for the standard deviation of l.o.p. values have been obtained by Pierce[62] and Swanson and Tibbals[63] and it is this characteristic of *Omega* to show small variability in its l.o.p.s on a world-wide basis that gives rise to its anticipated widespread use as a navigation aid.

An important aspect of the *Omega* system is the ability to predict and correct for the 'stable' propagation effects. Swanson[64] has reviewed the techniques used to

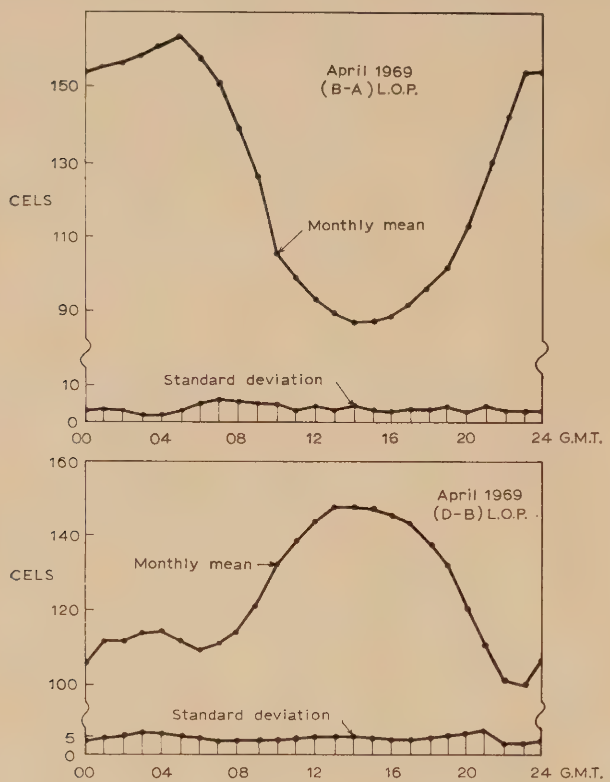



**Fig. 12.** Monthly mean value and standard deviation for the (B–A) and (D–B) *Omega* l.o.p.s measured at Farnborough, U.K.

do this and only some aspects of this large problem are touched on here.

### 4.2.3 *Problems of lane resolution*

For sufficiently slow moving vehicles, the ability to resolve the 15 km position line ambiguities of the 10·2 kHz transmissions is not paramount and reception of only one frequency may be sufficient for most purposes. With appropriate corrections for diurnal variations in the phase delay an accuracy approaching 1–2 km may be achieved. However, for quickly moving vehicles use of three or more frequencies of transmission will probably be necessary in order to resolve completely all the ambiguous position lines. The three *Omega* transmission frequencies of 10·200, 11·333 and 13·600 kHz allow the 1133 and 3400 Hz resolving frequencies to be used for position line resolution, with corresponding position line spacings of 135 and 45 km. The important question then arises of whether the phase variability of the resolving frequencies is sufficiently small to allow the appropriate position line in the next finer mesh of position lines to be unambiguously determined.[64,65]

One of the main sources of phase variability in v.l.f. propagation is that of interference between the two propagating waveguide modes. Because of the lower attenuation rates of the waveguide modes at night, this interference effect will be strongest under these conditions. It is extremely difficult to measure the phase-delay variation with distance of a single carrier frequency, but the difference in phase delay between two close transmission frequencies as a function of distance is amenable to measurement and is in fact the required parameter to evaluate the variability of the resolving frequencies.

Measurements taken on transmissions from *Omega* Trinidad on 13·600 kHz, phase modulated at 226·67 Hz, and also on the pair of frequencies 10·200 and 10·462 kHz, enabled a study of the phase delay variability of the experimental resolving frequencies of 226·67 and 262 Hz to be made as a function of distance from the transmitter. Some results of these measurements[65] indicate that the amount of second mode present at night at considerable distances from the transmitter (up to 7000 km) is very much greater than theory originally predicted (Fig. 13). In fact the magnitude of the phase delay variations of these resolving frequencies under night conditions are such that the position lines laid down by the 1133 Hz frequency may not be resolved using the lower frequency. Under day conditions the corresponding phase delay variability is smaller by nearly an order of magnitude and position line resolution is then entirely feasible.

### 4.2.4 *Effects of the Earth's surface*

The major portion of the Earth's surface is covered in water, and as far as v.l.f. propagation is concerned, behaves as a perfect conductor. When propagation occurs over the land surfaces of the Earth the waves propagate with higher attenuation rates but it is only in areas of extremely low conductivity, such as the ice-cap regions of the world, where the attenuation rates become excessive (of the order 20–40 dB/Mm).[67,68] Loss of signal is then likely for paths transversing the Greenland ice-cap or Antarctica, and hence puts a limitation on the number of position lines available in areas close to such ice-caps.

The phase velocity of the propagating signal can also be affected when the waves cross a conductivity discontinuity on the Earth's surface, such as a coast line. Indications are that in the context of the accuracy of *Omega* quoted in preceding sections this effect is not important, but may become so if use is made of *Omega* in its differential mode of operation. Figure 14 illustrates

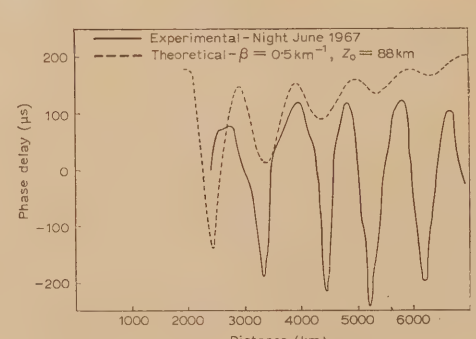
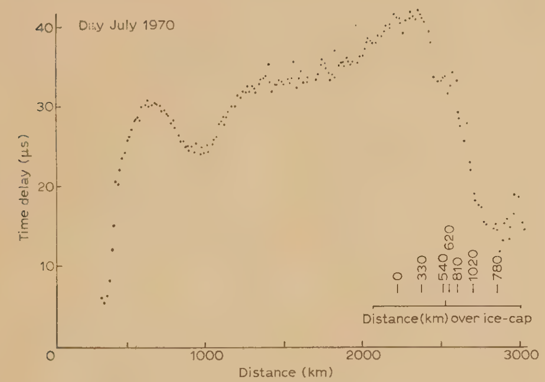
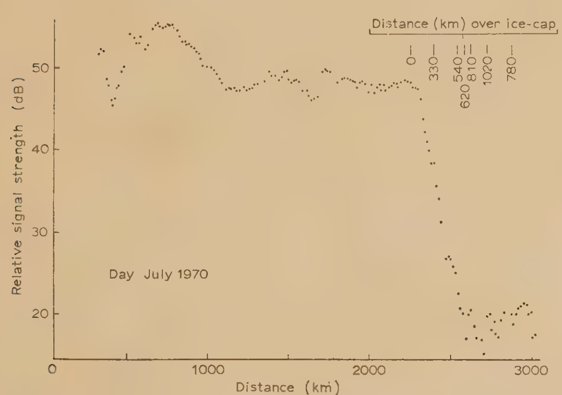



**Fig. 13.** Phase delay variability of the 262 Hz difference frequency referred to a 10·2 kHz carrier as a function of distance from the transmitter (*Omega* Trinidad). Night conditions.




(a) Time delay of 13·6 kHz relative to 10·2 kHz as a function of distance from transmitter *Omega* Norway showing effect of Greenland Icecap.




(b) Signal strength at 13·6 kHz as a function of distance from the *Omega* Norway transmitter. Effect of Greenland Icecap is shown.

**Fig. 14.**

the effects of the Greenland ice-cap on the phase and amplitude of signals transmitted from *Omega* Norway.

In propagating over large extents of land the phase velocity is decreased on its sea path value by some 0·05–0·10% where the conductivity lies between $10^{-2}$ and $3\times10^{-3}$ S/m which is typical of the major portion of continents. Over a land path of some 5000 km this would result in an error of some 5 km. This type of error is probably amenable to being calibrated out of the system.

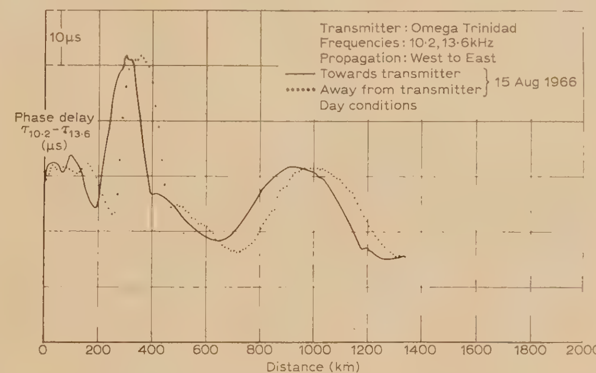
### 4.2.5 *Closeness to transmitter, and non-reciprocal propagation*[69]

The modes excited by a v.l.f. transmitter propagate with different phase velocities and consequently give rise to a series of maxima and minima in the field strength of the received signal as one moves away from the transmitter. As one travels through a minima in the field strength pattern the phase of the received signal changes; the deeper the minima the more rapid and greater is the phase change.

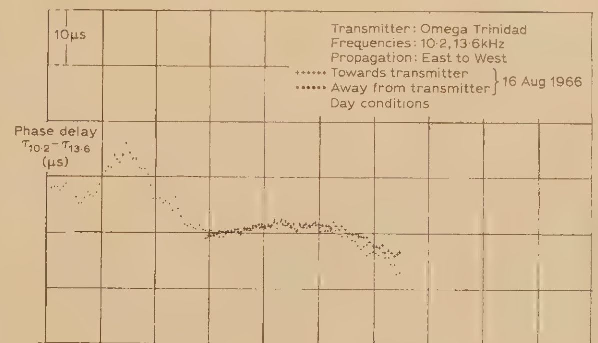
Under day conditions, at 10·2 kHz, one may experience up to $\pm25$ μs change in the time delay of the received signal as one passes through the deepest minimum in field strength. This would be equivalent to an error of $\pm4$ km in an l.o.p. over a range of some 200–500 km from the transmitter.

At night this modal interference can be more severe and it is possible at 10·2 kHz for propagation towards magnetic East, for the second mode to dominate over the first mode beyond the position of the first minimum in field strength. Consequently, at a greater range, when the first mode is dominant, the phase error is at least one cycle (or a l.o.p. is in error by one position line, 15 km) when reference is made to single mode propagation. This magnitude of errors occurs over a distance of some 400–700 km from the transmitter; smaller errors occurring at ranges out to some 2000 km from a transmitter.

Figure 15 illustrates this effect for day-time conditions where the relative phase-delay of the 10·2 kHz and 13·6 kHz transmissions from *Omega* Trinidad are plotted. This also shows the marked non-reciprocal propagation characteristics of v.l.f. propagation where propagation towards the magnetic West is attenuated more severely than towards the magnetic East, the difference under day conditions at 10·2 kHz being some 4 dB/Mm




(a) Relative phase delay of 10·2 and 13·6 kHz signals as a function of distance from the *Omega* Trinidad transmitter. Daytime conditions West to East propagation.




(b) Relative phase delay of 10·2 and 13·6 kHz signals as a function of distance from the *Omega* Trinidad transmitter. Daytime conditions East to West propagation.

**Fig. 15.**

(6 dB/Mm, West; 2 dB/Mm, East). This fact, together with the lower attenuation by night than by day, results in a 10·2 kHz signal propagating to the magnetic West being attenuated to a level comparable to the signal propagating to the magnetic East at some 10 Mm to the West of the transmitter. Thus as well as an area at the antipodes, there will exist an area, for transmitters situated in low latitudes, some 10 Mm to the magnetic West of the transmitter, where the phase of the received signal may be unstable—due to the interference between signals arriving by more than one propagation path.

### 4.2.6 *Effect of solar disturbances*

Disturbed propagation conditions can be classed into two main groups. First there are the sudden phase anomalies (s.p.a.) which are associated with x-ray bursts from solar flares, (see Sect. 3) and occur simultaneously with the short wave fade outs on high frequencies. Figure 16 shows a histogram of the number of s.p.a.s observed in the year 1968 as a function of the maximum phase delay suffered for propagation over the *Omega* Trinidad to Farnborough path. Some 350 s.p.a.s were observed over this period and the average maximum phase delay was 10 μs. This would be reflected as a maximum variation of a l.o.p. appropriate to Farnborough, of 1·5 km if the second propagation path involved did not suffer an effect. This will not usually be the case and the magnitude of the l.o.p. variation will be somewhat less than 1·5 km for this particular l.o.p. Further, this is a maximum effect, which will last for only a few minutes on average, and as a guide to the duration of the effect, for s.p.a.s having maximum phase delays greater than 40 μs, the phase delay is greater than 20 μs for approximately 40 min, while for s.p.a.s of magnitude greater than 20 μs, the phase delay is greater than 10 μs for some 20 min. Over the whole year of 1968, which is a year of maximum solar activity for the present sunspot cycle, 3·6% of the time was affected to some degree by s.p.a. effects; however only 0·3% of the time showed a phase delay in excess of 20 μs which would show up as a variation not greater than 3 km in a l.o.p. measured at Farnborough which included the *Omega* Trinidad transmitter as one of the measuring stations. It is interesting to note that the two largest s.p.a.s indicated a maximum phase delay of 70 μs (maximum l.o.p. variation of 10 km).

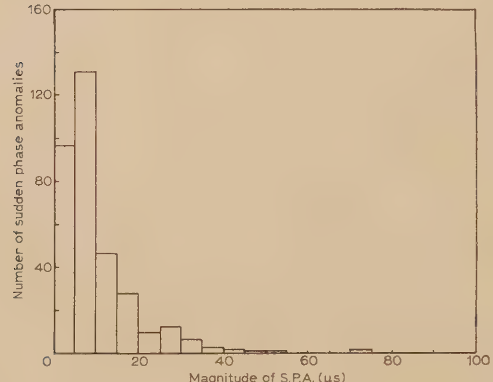



**Fig. 16.** Histogram relating the number and magnitude of sudden phase anomalies observed on the *Omega* Trinidad–Farnborough path. 7100 km 10·2 kHz.

The second class of disturbances are more infrequent than s.p.a.s and refer to disturbances produced in the lower ionosphere over polar regions by high energy solar particles; in certain extreme cases extending down to latitudes lower than the auroral zone by some 5–10 degrees. While these disturbances are relatively infrequent, their effect on v.l.f. propagation can last for several days. In 1968, ten such solar proton events resulting in large disturbances to v.l.f. propagation over polar regions were observed at Farnborough, occurring on a total of 43 days of the year. Similar to solar flare effects, no loss of signal is observed at 10·2 kHz during such disturbances and the phase delay decreases. The magnitude of this decrease during daylight conditions over the propagation path is a maximum on the first day of the event and slowly recovers to quiet conditions during the succeeding days. Maximum phase delays from 10–60 μs have been observed and, in a similar manner to solar flare effects, can be interpreted in terms of l.o.p. variations.

## 4.3 Other Applications

Navigational applications discussed above relate to the lower end of the v.l.f. band; the higher frequencies (14–30 kHz) are used for communication and standard frequency/timing purposes. The general features of v.l.f. propagation discussed in relation to the navigation application carry over to these higher frequencies, the main change in characteristic being due to the lower attenuation of the higher-order waveguide modes coupled with their higher relative excitation factors. Thus modal interference, as observed in field strength plots against distance and dawn and dusk transitions in signal amplitude and phase measurements, are considerably enhanced as illustrated in Fig. 17 as compared with the lower frequencies. The implications here are that prediction of propagation loss will be more difficult and one would expect more variability in temporal and spatial characteristics. These shortcomings have to be traded against available bandwidth and antenna efficiencies as the frequency is increased. Further illustrations of the effects of the contribution of higher-order modes can be found in the papers of Johler[23] and Pappert and Bickel.[70]

On moving to higher frequencies (> 30 kHz) the waveguide mode concept of propagation becomes less useful and it is more appropriate to talk in terms of wave-hops (Section 2.3). Propagation at these frequencies is still highly stable compared with h.f. and the early work on the *Omega* type navigational aids took place at these low (l.f.) frequencies. The skywave propagation was shown in general to be too unstable for this use, though systems such as *Decca* and *Loran C* employ these frequencies. The difference which these systems underline is that higher accuracies can be obtained than at v.l.f. but their range is limited to essentially ground wave cover. This is relatively small over land masses but can extend, in

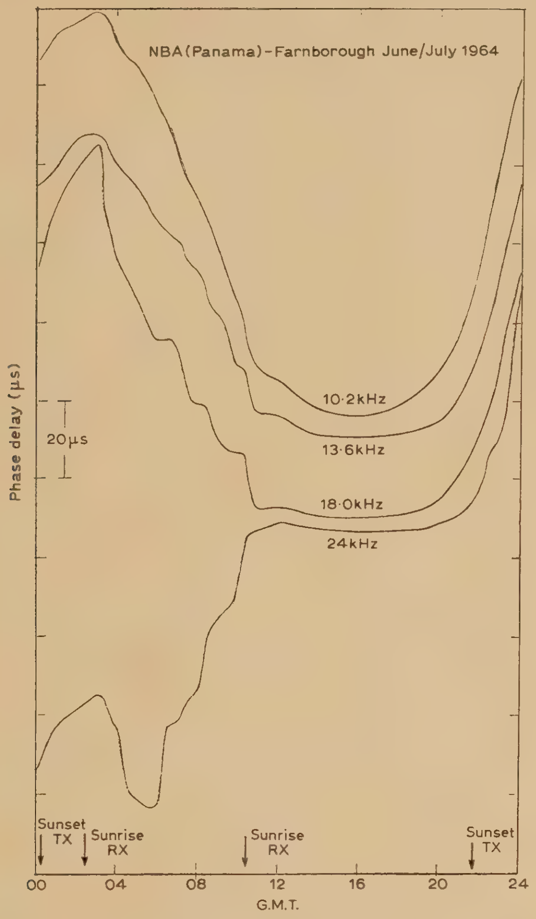



**Fig. 17.** Diurnal phase delay variations for various frequencies.

the case of *Loran C* to over 1500 km for sea-water propagation.

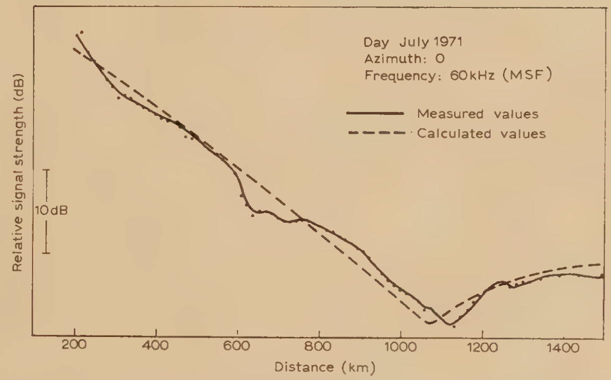
Low frequencies are used for low-speed data communications where high reliability is needed as has been discussed by Williams and Ince.[71] This is particularly so in high latitudes, where disturbances to the ionospheric and E and F regions make h.f. communications notoriously unreliable, especially in times of high sunspot activity; l.f. on the other hand suffers relatively small effects due to solar disturbances in the lower ionosphere.

As an indication of the propagation characteristics of l.f. signals over 1000–2000 km, Figs. 18(a) and((b) show signal level plots against range for 60 kHz transmissions under day and night conditions. Daytime conditions show very stable conditions with a stable interference pattern, while the night-time curve indicates strong sky wave interference starting at about 200 to 300 km from the transmitter. Experimental data such as these are rare and more data are needed in this area if a good understanding of l.f. propagation and its influence on communications system performance is to be assessed.

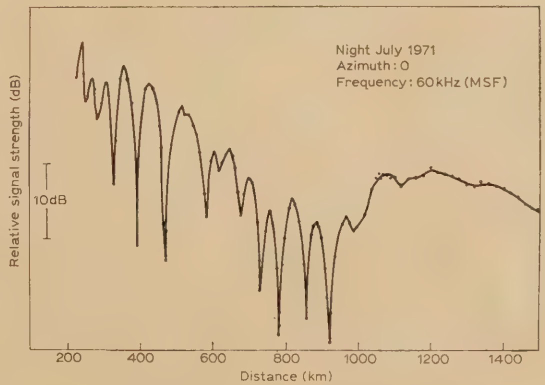
## 5 Concluding Remarks

In this paper the various theoretical analyses available for calculating the propagation characteristics from model ionospheres have first been reviewed. These techniques enable the phase and amplitude of the received signal to be calculated for any given locations of the transmitter and receiver, subject to the limitations of the ionospheric model employed. Recent developments have enabled complicating features such as variable ground conductivity and the influence of the dawn-dusk line to be included in these calculations. The calculated propagation parameters are in good agreement with those determined experimentally and all the major features observed are reproduced in the computed results. The ability to calculate the received signal parameters is clearly of major importance in designing any navigation or communications system.

The propagation characteristics of v.l.f./l.f. waves have been studied experimentally for many years. Details are given of the development of these researches and of the present state of our knowledge. The high degree of amplitude and phase stability obtainable in this frequency band, particularly at v.l.f., render it ideal for navigation purposes. Systems applications of v.l.f./l.f. propagation are discussed but clearly it has not been possible to include a detailed account of every sort of application. One system, the *Omega* navigation system, has been selected for detailed discussion since this clearly




(a) Signal strength variation with distance from a 60 kHz transmitter (MSF). Daytime conditions.




(b) Signal strength variation with distance from a 60 kHz transmitter (MSF). Night-time conditions.

**Fig. 18.**

demonstrates the use of the special features of the v.l.f. propagation.

Further applications of v.l.f./l.f. waves are to be expected in the future particularly in the areas of sub-surface communications and in geological applications. High phase and amplitude stability, low attenuation rates, and high reliability are unique to this frequency band and these important characteristics will clearly feature in future developments.

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*Manuscript received by the Institution on 22nd July 1974 (Paper No. 1623/Com. 104).*

# STANDARD FREQUENCY TRANSMISSIONS

*(Communication from the National Physical Laboratory)*

## November 1974

| Nov. 1974 | Deviation from nominal frequency in parts in $10^{10}$ (24-hour mean centred on 0300 UT) | | | Relative phase readings in microseconds NPL—Station (Readings at 1500 UT) | |
|---|---|---|---|---|---|
| | GBR 16 kHz | MSF 60 kHz | Droitwich 200 kHz | *GBR 16 kHz | †MSF 60 kHz |
| 1 | 0 | 0 | −0·1 | 701 | 603·4 |
| 2 | +0·1 | −0·4 | −0·1 | 700 | 603·8 |
| 3 | −0·1 | 0 | −0·1 | 701 | 603·8 |
| 4 | 0 | 0 | −0·1 | 701 | 603·8 |
| 5 | 0 | 0 | −0·1 | 701 | 603·8 |
| 6 | 0 | 0 | −0·2 | 701 | 603·8 |
| 7 | 0 | −0·1 | −0·2 | 701 | 603·9 |
| 8 | +0·1 | 0 | −0·2 | 700 | 603·9 |
| 9 | 0 | +0·2 | −0·2 | 700 | 603·7 |
| 10 | 0 | 0 | −0·2 | 700 | 603·7 |
| 11 | −0·1 | −0·1 | −0·2 | 701 | 603·8 |
| 12 | −0·1 | −0·1 | −0·1 | 702 | 603·9 |
| 13 | −0·2 | 0 | −0·1 | 704 | 603·9 |
| 14 | 0 | 0 | −0·2 | 704 | 603·9 |
| 15 | +0·2 | −0·1 | −0·2 | 702 | 604·0 |
| 16 | −0·2 | −0·1 | −0·2 | 704 | 604·1 |
| 17 | 0 | −0·1 | −0·2 | 704 | 604·2 |
| 18 | 0 | −0·3 | −0·2 | 704 | 604·5 |
| 19 | 0 | +0·1 | −0·2 | 704 | 604·4 |
| 20 | 0 | +0·1 | −0·2 | 704 | 604·3 |
| 21 | 0 | 0 | −0·2 | 704 | 604·3 |
| 22 | 0 | 0 | −0·2 | 704 | 604·3 |
| 23 | 0 | 0 | −0·2 | 704 | 604·3 |
| 24 | 0 | 0 | −0·2 | 704 | 604·3 |
| 25 | 0 | 0 | −0·2 | 704 | 604·3 |
| 26 | 0 | +0·1 | −0·2 | 704 | 604·2 |
| 27 | 0 | 0 | −0·2 | 704 | 604·2 |
| 28 | 0 | −0·2 | −0·2 | 704 | 604·4 |
| 29 | 0 | +1·2 | −0·2 | 704 | 603·2 |
| 30 | 0 | 0 | −0·2 | 704 | 603·2 |

## December 1974

| Dec. 1974 | Deviation from nominal frequency in parts in $10^{10}$ (24-hour mean centred on 0300 UT) | | | Relative phase readings in microseconds NPL—Station (Readings at 1500 UT) | |
|---|---|---|---|---|---|
| | GBR 16 kHz | MSF 60 kHz | Droitwich 200 kHz | *GBR 16 kHz | †MSF 60 kHz |
| 1 | −0·1 | 0 | −0·2 | 705 | 603·7 |
| 2 | +0·2 | +0·1 | −0·2 | 703 | 602·4 |
| 3 | 0 | 0 | −0·3 | 703 | 602·2 |
| 4 | +0·1 | 0 | −0·2 | 702 | 602·4 |
| 5 | 0 | 0 | −0·2 | 702 | 602·6 |
| 6 | +0·1 | 0 | −0·2 | 701 | 602·8 |
| 7 | −0·1 | 0 | −0·2 | 702 | 602·8 |
| 8 | 0 | 0 | −0·2 | 702 | 603·0 |
| 9 | 0 | 0 | −0·3 | 702 | 603·2 |
| 10 | 0 | 0 | −0·2 | 702 | 603·4 |
| 11 | 0 | 0 | −0·2 | 702 | 603·6 |
| 12 | 0 | 0 | −0·2 | 702 | 603·2 |
| 13 | 0 | 0 | −0·2 | 702 | 603·4 |
| 14 | 0 | 0 | — | 702 | 603·2 |
| 15 | 0 | 0 | — | 702 | 603·4 |
| 16 | 0 | 0 | −0·3 | 702 | 603·2 |
| 17 | 0 | 0 | −0·1 | 702 | 603·2 |
| 18 | +0·1 | 0 | −0·3 | 701 | 603·4 |
| 19 | 0 | 0 | −0·3 | 701 | 603·6 |
| 20 | 0 | 0 | 0 | 701 | 603·8 |
| 21 | 0 | 0 | 0 | 701 | 604·1 |
| 22 | 0 | 0 | 0 | 701 | 604·1 |
| 23 | 0 | 0 | 0 | 701 | 604·1 |
| 24 | 0 | 0 | 0 | 701 | 604·2 |
| 25 | 0 | 0 | −0·1 | 701 | 604·0 |
| 26 | 0 | 0 | 0 | 701 | 603·9 |
| 27 | +0·2 | 0 | 0 | 699 | 604·0 |
| 28 | −0·1 | 0 | 0 | 700 | 604·1 |
| 29 | −0·1 | 0 | 0 | 701 | 604·1 |
| 30 | 0 | 0 | 0 | 701 | 604·1 |
| 31 | 0 | 0 | 0 | 701 | 604·1 |

All measurements in terms of H-P Caesium Standard No. 334, agrees with the NPL Caesium Standard to 1 part in $10^{11}$.

* Relative to UTC Scale; $(UTC_{NPL}$ — Station) = + 500 at 1500 UT 31st December 1968.

† Relative to AT Scale; $(AT_{NPL}$ — Station) = + 468·6 at 1500 UT 31st December 1968.

UDC 621.391.812.63:621.396.677.51

# Ionospheric perturbations and their effect on the accuracy of h.f. direction finders

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and

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SUMMARY

The principles of high frequency direction finding are briefly described and the main sources of error in these systems discussed. The deviations in bearing produced by travelling ionospheric disturbances (t.i.d.s) are considered in detail since these errors are particularly difficult to predict and correct. General background information on the physics of t.i.d. phenomena has been included and attention given to the source mechanism and propagation characteristics of the disturbances. The paper concludes with a review of some possible methods for the correction of t.i.d. induced errors and details are given of some recent investigations of error correction procedures.

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## 1 Introduction

It is now possible to design h.f. direction finders with an instrumental accuracy of better than 0·1 degrees standard deviation. Unfortunately, in practice, when making d.f. measurements on ionospherically propagated signals, this intrinsic high accuracy cannot be realized due to the perturbations and tilts which exist in the reflecting medium.

One of the main causes of d.f. inaccuracy has now been shown to be travelling ionospheric disturbances (t.i.d.s), and these events have been the subject of intensive study over the last few years. This paper, after a brief resumé of the principles of h.f.d.f. and a statement of the main sources of error, gives a detailed description of the physics, morphology and methods of observing t.i.d.s. In particular, the results of a protracted series of observations undertaken by the authors over the last few years are presented. This is followed by a Section describing techniques which are currently being developed for reducing errors in h.f.d.f.

## 2 Principles of High Frequency Direction Finding

Most h.f.d.f. systems depend on the principle of determining the direction of the normal to the phase front of the arriving wave. The simplest possible form of h.f.d.f. system would be a pair of omni-directional aerials mounted on a rotating boom, the outputs of the aerials being fed to a difference hybrid. In order to find the azimuthal angle of arrival of an incident wave, the system is rotated to give a zero output from the hybrid. For this condition, the two aerials must be located on an equi-phase front and the required azimuthal angle can then be read off a suitable bearing scale. The Adcock system[1,2] uses the same principle but deploys pairs of orthogonal aerials, each element of a pair being at opposite ends of a diameter of a circle around which the pairs are symmetrically placed. The aerial pairs are interpolated by means of a rotating goniometer.

There are numerous types of h.f. direction finder but it would not be appropriate in this paper to do more than mention the various broad classification of types of systems.

A much used type is the interferometer, where angle of arrival information is obtained by the measurement of the phase difference between two spaced aerials. A single phase measurement will define a cone on which the normal to the phase front must lie. Two intersecting cones, derived from two orthogonal pairs of aerials, will define the angle of arrival in both azimuth and elevation.[3] Ambiguities in determining the cone angles arise as the spacing of the aerial pairs is usually large compared with a wavelength and means of resolving the ambiguities have to be provided.

Various systems have been developed which make use of the Doppler principle. For example, a vertical aerial mounted on an arm rotating in a horizontal plane will impart a frequency modulation on the arriving signal due to the circular motion of the aerial. The azimuthal

angle of arrival can be deduced from the phase of the modulation relative to a fixed reference. Another version of this system uses a ring of static aerials and cyclically samples phase in each aerial.[4] This is known as the commutated antenna direction finder (c.a.d.f.).

The most modern systems of h.f.d.f., however, use circular arrays of relatively large diameter[5] from which narrow beam scanning aerials are formed in a rotating beam forming network (goniometer). It is with the errors of this type of system that this paper is concerned. A typical system might employ a ring of say 96 aerials, which may themselves be directional, symmetrically disposed on a circle of 300 m diameter.

In one such system, the outputs from two adjacent arcs of 16 aerials are coherently and separately summed by two delay line systems mounted on the rotor of the goniometer. When the goniometer is pointing in the direction of the wave normal the voltages from the arc of aerials add in phase. The outputs are taken via rotating transformers to a sum-difference hybrid, the sum output giving a $\sin x/x$ type polar diagram, whilst the 'difference' output gives a polar diagram with a deep 'notch' corresponding to the position of the beam maximum of the 'sum' polar diagram. Direction finding may be executed automatically by digitizing and storing in a computer the 'difference' (or sum) output from the spinning goniometer. The angle of arrival can be deduced, in real time, by means of a suitable computer algorithm which calculates the position of the 'notch' (or maximum) relative to the angular position of the goniometer. Such an automated d.f. system is ideal for studying the fluctuations in the azimuthal angle of the signal as bearings can be measured sequentially over many hours and the results automatically plotted or stored for further processing. This type of h.f.d.f. which employs a large circle of aerials is known as a wide-aperture d.f. system (w.a.d.f.).

## 3 Sources of Error in Wide Aperture Direction Finders

As stated, w.a.d.f. systems can now be constructed with instrumental errors such that the standard deviation of the error curve, taken over all azimuths and a 2 octave frequency range, is as low as 0·1 degrees. The instrumental errors are usually measured by radiating signals, either from a helicopter within line of sight, or from a vehicle-borne mobile transmitter within ground wave range. When measuring the azimuths of ionospherically propagated signals, however, the accuracy of the system is found to be considerably less than that obtained for ground wave signals and a typical figure for the variance would be 2 to 4 degrees squared depending on the range. Following the early pioneering work of Bramley and Ross using interferometer d.f. systems,[6–9] the most significant sources of error have now been identified.[10] These are the solar related lateral tilts of the ionosphere (l.a.t.s.) and the perturbations of the ionosphere which have become known as travelling ionospheric disturbances (t.i.d.s) and are almost certainly due to acoustic-gravity waves.[11–17] The errors in w.a.d.f. due to both these causes have over the last few years been measured in detail and in general, about one-third of the variance can be attributed to l.a.t.s or s.i.t.s (systematic ionospheric tilts) as they are sometimes called, and about two-thirds to t.i.d.s. This ratio is however very variable depending on the state of the ionosphere, the azimuth of the arriving waves, the time of day, the season and the geophysical conditions. On some occasions most of the variance is due to t.i.d.s whilst at others the errors due to s.i.t.s are predominant.

In addition to the d.f. errors due to s.i.t.s and t.i.d.s, there is also error caused by wave interference (w.i.). This occurs when more than one wave front can arrive simultaneously at the direction finder via different 'paths' or modes of propagation and at slightly varying azimuthal angles. The differential azimuths can occur, either by virtue of the fact that different modes may be reflected from separate layers which are unequally tilted, or because modes arrive after different numbers of reflexions from the ionosphere. As the bearing deviation due to tilt depends on the number of hops, modes with different numbers of hops will therefore arrive from slightly different azimuthal angles. Finally, different modes may not all be affected equally by t.i.d.s which may be present. The effect of two waves of identical frequency but different azimuths impinging on an h.f. direction finder is to cause a d.f. error which depends on the phase angle between the two signals. Due to turbulence (t.i.d.s etc.) and relative movement in the ionosphere the phase is not constant and the bearing error deviates about a mean, a phenomenon known as wave interference. Wave interference in an h.f.d.f. system is analogous to the fading which affects most h.f. signals and arises from the same basic cause, i.e. multi-mode propagation. Wave interference is not nearly so important a source of d.f. error as s.i.t.s or t.i.d.s because the frequency of oscillation of the bearing deviations is usually greater than 1 Hz and most of the error can be removed by averaging the bearings over a few seconds. The mean bearing after averaging tends to that of the strongest signal.

Due to the fact that t.i.d.s are normally the greatest source of d.f. error, recent h.f.d.f. work has been concentrated mainly in studying t.i.d.s and on devising schemes to overcome t.i.d.-induced bearing errors. Before describing these schemes, the next Section will summarize the current state of knowledge of t.i.d.s and will describe monitoring systems which have been used for observing and recording t.i.d. activity.

## 4 Travelling Ionospheric Disturbances

The large-scale changes which occur in the ionosphere due to diurnal, seasonal and solar cycle variations, are reasonably well understood and can be fairly accurately predicted. Superimposed on these global and long term variations in the ionization distribution are a number of relatively small irregularities which exist at all levels in the ionosphere. These range in size from hundreds of metres to hundreds of kilometres and are readily observed since they move and have component velocities in the vertical and horizontal directions which can be measured. Horizontal velocities ranging from a few metres per second to over 1000 metres per second have been recorded for these so-called travelling ionospheric

**Table 1.** Classification of ionospheric irregularities (after G. H. Munro and T. M. Georges)

| Type | Size | Number | Method of Observation | Instrument | Elongation | Motion |
|---|---|---|---|---|---|---|
| large | $10^2-10^3$ km | single or train | virtual height or horizontal gradient | ionosonde or satellite | EW | NS |
| medium | $10-10^2$ km | single or train | virtual height or focusing | fixed freq. $h'$ wide space, h.f. Doppler | EW<br>NS | NS<br>EW |
| small | $1-10$ km | longer trains | focusing or diffraction | fixed freq. $h'$ close space, h.f. Doppler | NS | EW |
| very small | $10^{-1}-1$ km | families | diffraction | single station interferometer | — | — |

disturbances (t.i.d.). The characteristics of the various types of t.i.d. have been summarized by Munro[18] and their major features are indicated in Table 1. The present paper is concerned mainly with the medium and large-scale disturbances since these give rise to significant errors in the bearings obtained by h.f. direction finders. Some reference is made to small-scale disturbances in tracing the chronological development of the subject.

The formation of travelling disturbances is not well understood and many physical processes may contribute to their production and propagation. For example, the driving forces may be electro-dynamic forces such as those associated with plasma instabilities or, alternatively, motions of the neutral air could play a dominant role in this process. It is generally agreed that the medium and large-scale events result from the propagation of internal gravity waves through the atmosphere. The passage of these waves distorts the iso-ionic contours and therefore produces a displacement of the reflexion point of a radio wave propagated through the medium. It is these movements in the reflexion region that create the bearing errors which are associated with t.i.d. activity.

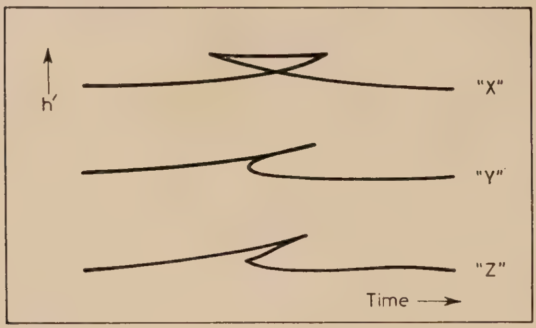
Various names have been given to the many types of waves which occur in the neutral atmosphere. High-frequency longitudinal (compression) waves are called acoustic waves since their frequencies lie in the audio range. Waves of frequencies less than the audio limit are referred to as infrasonic. When the frequency becomes very low, the effects of atmospheric density stratifications become a major factor in the propagation of the waves and they are then described as acoustic-gravity waves. In these internal gravity waves, the air particle motions have components transverse to the propagation direction. Even larger waves, thousands of kilometres long, have been detected in the atmosphere. These horizontally transverse waves are associated with global weather systems and are known as 'planetary' waves. The medium- and medium/long-scale waves produce bearing errors which are difficult to correct and the properties of these disturbances are therefore discussed at some length in a later Section of this review.

### 4.1 Methods of Observing T.I.D.s

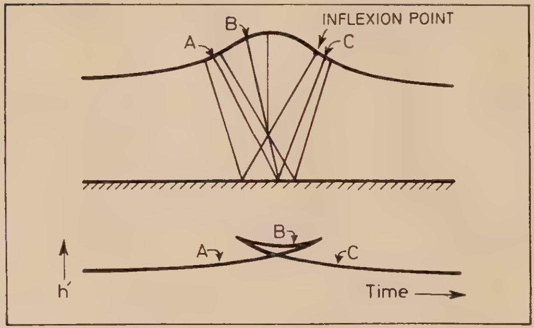
The influence of ionospheric movements on radio propagation has been recognized since the earliest days of radio.[19] Travelling disturbances produce distortions of the iso-ionic contours which give rise to focusing, defocusing, and height changes which in turn produce observable effects on reflected signals which vary with time.

For small-scale irregularities, the ionosphere can be considered as a diffracting screen, producing a diffraction pattern over the surface of the earth. By observing the signal fluctuations at a number of points on the ground, Ratcliffe and Pawsey[20] showed that information could be deduced regarding the speed and direction of the irregularities together with some measure of their magnitude. This technique was developed by Mitra[21] who employed three receivers placed at the corners of a triangle, the sides of which were a few wavelengths long. This spacing ensured that the fading records obtained from each of the three observation stations were correlated, though displaced in time due to movements or 'drift' of the reflecting layer. Statistical methods for analysing this type of experimental data have been developed by several authors.[22,23] Alternative methods of investigating the diffracting screen created by small irregularities have been suggested. For example, radio star scintillation methods have been developed by Lawrence *et al.*[24], Booker[25] and Briggs.[26] In a variation of this technique a transmitter in an artificial satellite is used in place of the radio star source.[27] These procedures are designed for the study of small-scale travelling irregularities and since their effects on radio bearings can be removed by integration they will not be discussed further.

At F-region heights, much larger disturbances are present which occur both as single events and as trains of waves. The concept of a phase diffracting screen is difficult to apply in these cases but the speed and direction of the disturbances can still be determined by the spaced receiver method if separations of tens of kilometres are employed. This method has been extensively used by Munro,[28–30] Price[31] and Toman[32] for the study of medium- and large-scale t.i.d.s. In Munro's experiments, fixed frequency pulse transmitters were located at the corners of a triangle spaced about 30 km apart. The signals were received at a central receiver and the variations in the equivalent height ($h'$) of the three reflexion heights recorded as a function of time. Examples of the $h'(t)$ variations recorded by Munro during t.i.d. activity are reproduced in Fig. 1, together with the geometry he




(a) Three types of ($h'$, $t$) traces associated with travelling disturbances, identified by Munro.




(b) Geometry suggested by Munro to account for t.i.d. effects in $h't$ recordings.

**Fig. 1.** Equivalent height variations produced by travelling disturbances and explanation in terms of a moving concave reflector.

proposed to account for these observations. The so-called $Y$ and $Z$ traces are not symmetrical and a simple model based on a concave reflector will not account for these events. Some form of asymmetry must be introduced such as a tilt in the wave front as the disturbance propagates.

Other techniques have been used in the study of t.i.d.s. Bowles[33] showed that t.i.d.s could influence the incoherent scatter of v.h.f. waves from the ionosphere and this effect has now been observed by other workers, e.g. Dougherty and Farley.[34,35] The ground backscatter of radio waves is also influenced by medium- and large-scale t.i.d.s as reported by Valverde[36] and Hunsucker and Tveten.[37]

One of the most successful techniques for continuous monitoring of t.i.d. activity is, however, the so-called Doppler sounding method. The passage of a t.i.d. displaces the reflexion point of an h.f. wave reflected from the ionosphere. The frequency of the reflected wave will thus be changed slightly by the Doppler effect associated with the moving reflector. The magnitude of the Doppler shift will depend on the rate of movement, i.e. on the rate of change of phase path of the radio wave. If the speed and direction of the disturbance is to be determined, it is necessary to employ at least three spaced transmitters and a central receiver. A typical recording of Doppler signatures produced by a t.i.d. on four spaced transmitters, separated in frequency by intervals of about 3 Hz, is reproduced in Fig. 2. The velocity is determined from the time displacements and the geometry of the transmitting and receiving locations. Details of the experimental technique have geen given by Davies *et al.*,[38] Georges[39] and Jones.[40] The Doppler frequency shifts produced by medium-scale t.i.d.s have been shown to be consistent with the equivalent height variation reported by Munro for these events.[39,41] Extensive use of Doppler sounding has been made over the last few years at the University of Leicester and GCHQ Cheltenham in a cooperative investigation into the effects of t.i.d.s on bearing errors.[42]

## 4.2 The Morphology of T.I.D.s

Although the ionospheric effects of t.i.d.s have been observed by many different techniques, very few observations have been made over a sufficiently long period to produce a statistically significant picture of their behaviour. The work of Munro[28–30] probably represents the longest continuous study of t.i.d.s although other workers, e.g. Georges[43] and Davies and Jones,[44] have also investigated the diurnal and seasonal changes in t.i.d. activity and behaviour.

Some confusion exists regarding the basic properties of t.i.d.s and conflicting observations have been reported of their range of speeds, dominant size and their diurnal and seasonal behaviour. This situation was clarified to some extent by Tveten[67] who recognized that the velocity distribution of t.i.d.s had two peaks, one at about 150 m s$^{-1}$ and the other greater than 300 m s$^{-1}$. These low and high velocity events appeared to have rather different characteristics. The events with low velocities are the so-called 'medium-scale' disturbances extending some hundred kilometres or so and their propagation can be described in terms of internal gravity waves travelling through the ionosphere. The high velocity t.i.d.s are 'large-scale' disturbances, often thousands of kilometres in extent, and which are observed most frequently during night-time. The propagation of these large disturbances cannot be explained in terms of the same gravity wave mechanism which accounts for the medium-scale events. The contrasting properties of these two types of t.i.d.s have been discussed by Georges[39] and the principal differences are summarized in Table 2.

Herron[45,46] has investigated the dependence of t.i.d. velocity on the wave period. For large-scale events (velocity > 300 m s$^{-1}$), the velocity was found to decrease with increasing wave period. This is contrary to the behaviour of a horizontally-propagating internal gravity wave for which the velocity increases with period. The observed behaviour can, however, be accounted for in terms of gravity waves provided the wave front tilts as it propagates.[46]

The general diurnal and seasonal behaviour of medium-scale irregularities has been summarized by Munro from his eight years of observations in the southern hemisphere. He reports that the monthly mean t.i.d. velocity is directed to the SE in summer and to the NE in winter. For both summer and winter the observed frequency of

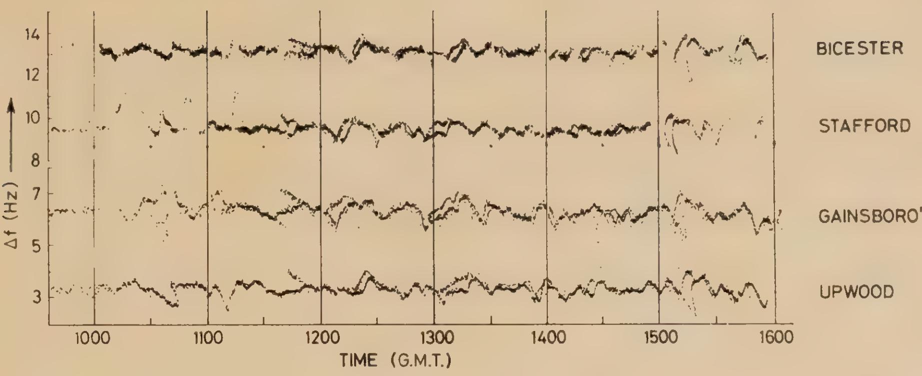



**Fig. 2.**
Typical daytime t.i.d. activity observed by the Leicester four-station Doppler.

occurrence of t.i.d.s maximizes at midday, and considerably more t.i.d.s are observed in winter than at other times of year. The scatter in the direction of travel of the t.i.d.s is a minimum in winter and large variations in direction occur in summer. This behaviour has been confirmed in the northern hemisphere by several workers, for example Jones.[40] These medium-scale t.i.d.s are well represented by the imperfectly ducted type of gravity wave discussed by Friedman.[47]

**Table 2.** Comparison of the properties of medium- and large-scale t.i.d.s

| Property | T.I.D. type | |
|---|---|---|
| | Medium scale | Large scale |
| Speed | $< 300\ \mathrm{m\ s^{-1}}$ | $> 300\ \mathrm{m\ s^{-1}}$ |
| Period | 10 to 40 min | > 30 min often exceeds 1 hour |
| Occurrence | mainly day time | day and night, mostly at night |
| Relationships with geophysical events | none | associated with geomagnetic activity |
| Characteristic features: | | |
| (a) Number of cycles | single events or trains of waves | 2 or 3 cycles only |
| (b) Wave front tilt | ~45° | nearly horizontal |
| (c) Shape | changes over distances of about 100 km | retained for thousands of kilometres |
| (d) Velocity/period relationship | velocity increases with period | velocity increases to a maximum then decreases with increasing period |

Less detailed information is available regarding the diurnal and seasonal behaviour of the large-scale t.i.d.s. They occur both in summer and winter and there is some evidence that they are more commonly observed at night. They are usually associated with geomagnetic storm activity and they appear to travel outwards from the polar regions. Very high velocities, sometimes in excess of $1000\ \mathrm{m\ s^{-1}}$, are recorded for these events. The form of the disturbances is preserved over great distances and varies little with the time of occurrence of the event. A typical example of such an event observed using the Doppler technique is reproduced in Fig. 3.

## 4.3 The Origin and Propagation of T.I.D.s

The general theory of the propagation of acoustic-gravity waves in the atmosphere has been reviewed by Tolstoy.[15] The interaction of gravity waves with the ionized atmosphere has been investigated both experimentally[48–55] and theoretically.[11–14, 55–60] Most of the

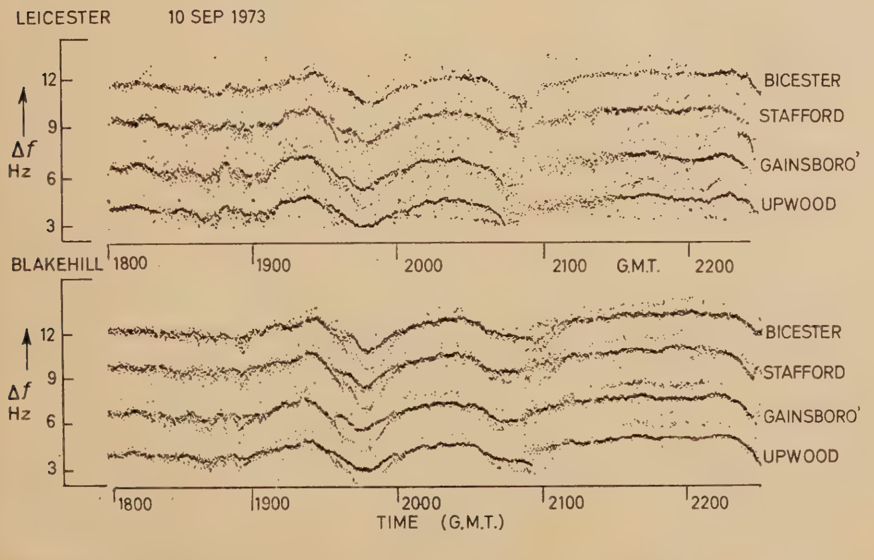



**Fig. 3.**
Examples of large-scale travelling waves observed during night-time at Leicester and Blakehill (near Cheltenham).

observed characteristics of t.i.d.s can now be explained in terms of internal gravity wave theory, especially when refinements such as the propagation in imperfect ducts[47] and the effects of neutral winds[61] are introduced.

Although considerable progress has been made in accounting for the propagation of t.i.d.s, relatively little is known about the sources and the generation of these disturbances. Georges[43] has suggested that the sources of the medium-scale t.i.d.s lie in the winter polar region and that they can propagate away from the source to great distances without appreciable attenuation. This would account for Munro's observations that in winter the t.i.d.s came from the south and in summer from the north. Further support for this suggestion comes from the fact that mesospheric heating occurs in the winter polar region.[62] This would allow gravity wave energy to penetrate upwards rather than being reflected in the mesophere. The action of Coriolis forces would influence the propagation of the t.i.d.s and would account for the overall eastwards shift in Munro's observations. The lack of medium-scale t.i.d.s during night-time has not yet been adequately explained. Georges[43] suggests that day/night differences may be due to differences in the electron density height gradient of the F-layer at these two times. Other factors, for example changes in the ion photochemistry, may also be involved in reducing the number of medium-scale t.i.d.s observed at night.

The large-scale t.i.d.s are associated with geomagnetic activity and several mechanisms for their production are possible. During geomagnetic storms, energetic particles are dumped at relatively low heights in the polar atmosphere and may create sufficient heating to generate long period waves. An alternative source may be the hydromagnetic effects associated with changes in the direction of the polar electrojet during storm activity. More than one production process may be involved and further investigations, particularly t.i.d. observations at high latitudes, are necessary before the sources of these disturbances can be isolated.

## 5 Methods of Correcting for T.I.D. Induced D.F. Errors

There is no known method of predicting in advance the precise occurrence and form of a t.i.d. Any correction system must therefore be based on a real time measurement of the t.i.d. at or near the time at which the bearing was measured. The measuring system must detect disturbances in or very near that region of the ionosphere traversed by the radio wave path from transmitter to direction finder.[66] Two methods have been experimented with and a third is currently being developed. These will be described in following Sections. The first involves a four-station Doppler network (as described in Sect. 4), positioned below the midpoint of the path between the transmitter and the d.f. system. This experiment demonstrated, not only that correlation between the bearing fluctuation and the Doppler detected t.i.d.s existed, but that a correction system was feasible.

The second experiment was based on the assumption that if one made sequential bearing measurements over a period of time on two (or more) transmitters spaced not too far apart, it would be expected that the bearing error time series would be correlated. Known errors on the one transmitter could then be used to correct for the errors on the other transmitter(s). This proposition has been found to be true but correlation coefficients high enough to make worthwhile short term corrections only occur infrequently. This suggests that the disturbances are themselves changing in shape as they proceed.

### 5.1 Correction by Vertical Incidence Doppler Measurements

It has always been generally accepted that the quasi-periodic variations (mean period 20 minutes) in the observed bearing have been associated with t.i.d. activity. This was to some extent a supposition, since until recently,[42] no experiment designed to relate unambiguously the presence of specific t.i.d.s to the bearing errors they produce had been undertaken. A net of Doppler frequency sounders (Sect. 4.1) was used to detect the presence of t.i.d.s and to determine their speed and direction. This particular experiment consisted of four standard frequency transmitters located at Upwood, Bicester, Stafford and Gainsborough (see Fig. 4), and a central receiver situated at Leicester. A fifth transmitter was sited at Patrington, near Hull, so that the reflexion point of the path from Hull to the direction finder (d.f.) situated in Wiltshire was well within the region of ionosphere monitored by the Doppler system. The frequency of the Hull transmitter was chosen to give approximately the same reflexion height in the ionosphere as the transmissions of the Doppler system. The experiment was carried out on 21st February 1973 when marked t.i.d. activity was present as illustrated in the Doppler recordings reproduced in Fig. 5. The bearings recorded by the direction finder are also included in the Figure and it is evident that considerable fluctuations occur which correlate well with individual t.i.d.s observed by the Doppler experiment. From the Doppler recordings, it was feasible to calculate the tilt at right angles to the Hull d.f. path and since the reflexion height was known from ionograms available at Leicester, it was possible to determine the bearing error produced by the t.i.d.s from the relationship

$$\Delta\theta = \frac{2h\phi}{d}$$

$h$ is the reflexion height, $d$ the path length, $\phi$ the tilt angle, and $\Delta\theta$ the bearing error. The bearing errors calculated in this way from the Doppler data were compared with the errors measured by the direction finder as shown in Fig. 5. Quite good agreement was obtained between the calculated and measured values. That the correlation was so good was surprising in view of the fact that the direction finder was operating under very unfavourable conditions. The minimum angle of arrival for 1-hop F would be about 60° whereas the system is optimized for 15–30° angles of arrival, and intense w.i., inevitable for such a short path, was present. Only by averaging many bearings could the dominant 1F dependent fluctuations be extracted. This experiment showed that

(1) T.i.d.s were indeed responsible for the 20 minute fluctuations observed in the measured bearing.

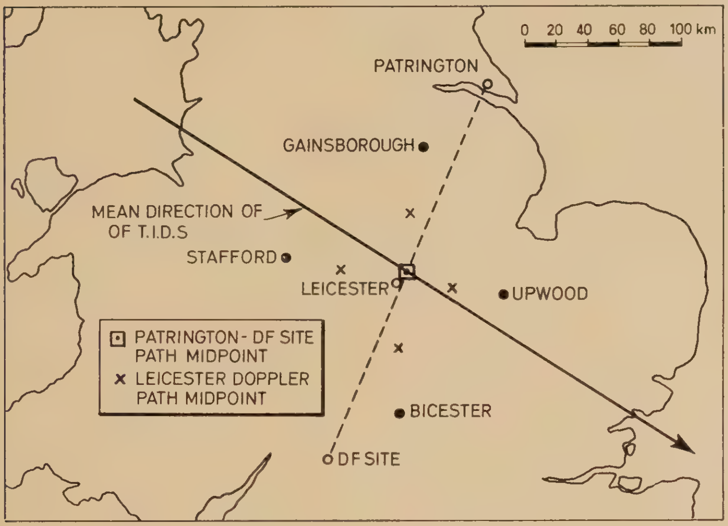



**Fig. 4.**
Distribution of transmitting and receiving sites used in Leicester four-station Doppler.

(2) It is possible to calculate the bearing error from a knowledge of the velocity and magnitude of the t.i.d.

### 5.2 Error Correction by Reference to Bearings of Known Transmitters

When propagation is by one dominant mode (uni-moded propagation or u.m.p.), the plot of the bearing of a given transmitter as a function of time (Fig. 6) shows the characteristic quasi-periodic fluctuations due to t.i.d.s coupled with a mean displacement attributed to s.i.t.[63] The t.i.d.s can be seen clearly but only when propagation is by a single mode (u.m.p.). Only then are successive measurements of error, (after removing the errors due to w.i.), correlated. When monitoring the bearing of a transmitter whose signals are received via multi-mode propagation (m.m.p.), a very confused plot is obtained. This is because of the turbulent nature of the ionosphere. At one moment, a dominant F-layer signal may prevail giving rise to a specific mean error. A few seconds later an E-layer signal with a different mean error may supervene to produce a sudden jump in the plotted error curve which is consequentially more 'noise-like' in nature. This presents a much more complicated problem because correction can only be attempted on individual modes and mode resolution in azimuth would first be necessary before this problem could be resolved. Very little published work on the multi-mode correction problem exists though mode resolution in azimuth has been achieved by several workers.[64, 65] This paper confines itself to the simpler question of error correction in the u.m.p. case.

If the t.i.d. had the form of a long wave-like corrugation, it might be assumed that bearings on two transmitters not too far distant from each other (100 km separation at a range of 1000 km say) might be similarly affected. If this were so, then knowledge of the bearing errors on a known transmitter might be used to correct the errors on a transmitter of approximately known position. Based on this idea, a series of measurements was made on many pairs of transmitters to see if the correlation of the error curves was sufficient to make a correction scheme feasible. Figure 6 shows one particular pair of error curves. It can be seen by eye, that correlation is excellent with maximum correlation coefficient obtained when the curves are time shifted by 4 minutes with respect to each

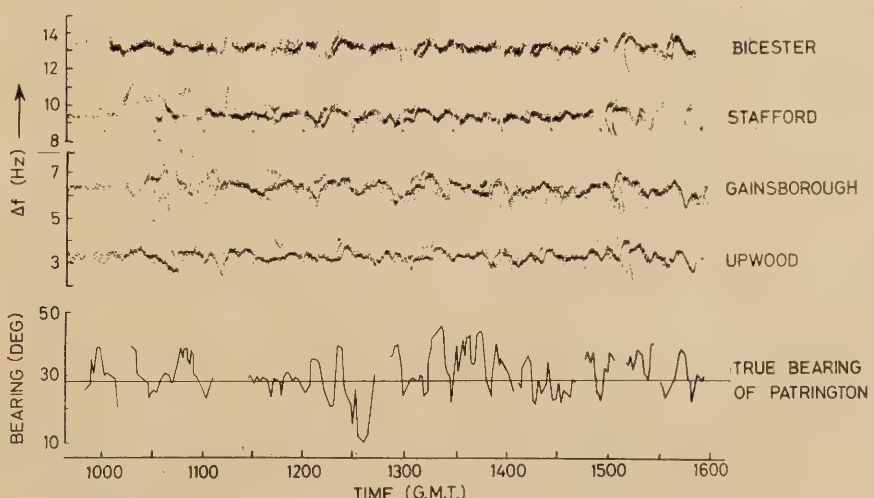



**Fig. 5.**
Comparison of the Doppler and bearing angle records for the 22nd February 1973 (Patrington) experiment.

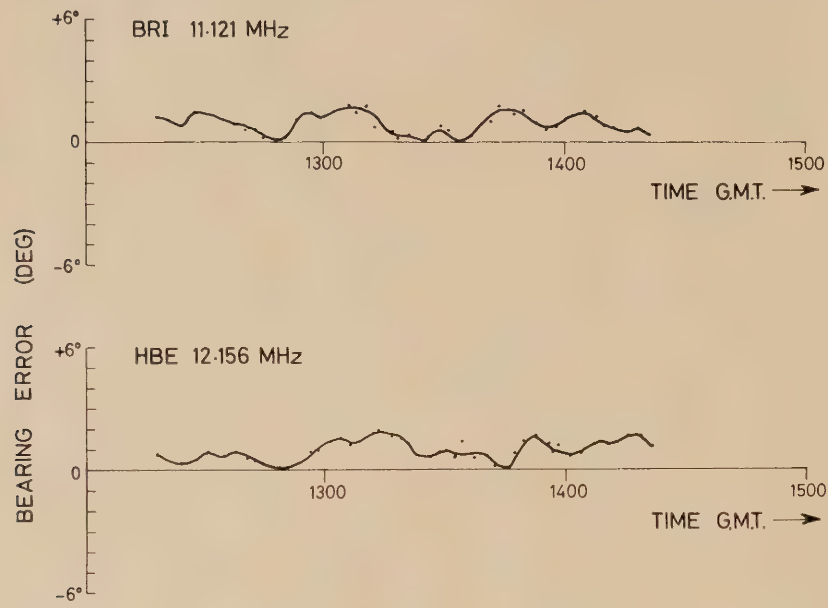



**Fig. 6.**
Correlation of bearing errors on two adjacent frequencies over approximately the same transmission path.

other. For this pair of transmitters the results in Table 3, measured over a 1-hour period, were obtained.

**Table 3.** Bearing corrections by error correlation (distant transmitters)

| | Without relative time shift | With optimim relative time shift |
|---|---|---|
| Variance on T1 | 1·9 | 1·5 |
| Variance ($\phi_1-\phi_2$) | 0·54 | 0·15 |
| Mean error T1 ($\bar{\varepsilon}_1$) | 1·46° | 1·29° |
| Mean error T2 ($\bar{\varepsilon}_2$) | 1·22° | 1·22° |
| $\bar{\varepsilon}_1-\bar{\varepsilon}_2$ | 0·24 | 0·07 |

In this particular case, the variance was reduced by a factor of $3\frac{1}{2}$ to 1 with no time shift prior to correcting, and 10 to 1 with time shift. This is not a typical result and such excellent corrections only occur on the few occasions when correlation is near to unity.

The relationship between variance improvement and correlation coefficients has been studied in more detail by Morgan and Reynolds[63] using bearing error measurements obtained from a group of co-located transmitters. Over a typical period of 1 hour the results given in Table 4 below were obtained.

**Table 4.** Bearing corrections by error correlation (co-located transmitters)

| Frequency separation between T1 and T2 | Maximum correlation coefficient | Minimum variance (deg$^2$) | Time shift for maxima and minima |
|---|---|---|---|
| 0·5 MHz | 0·95 | 0·06 | zero |
| 3 MHz | 0·97 | 0·1 | 3 min |
| 4·6 MHz | 0·94 | 0·2 | 5 min |

Excellent corrections are obtained and these results are typical for co-located transmitters with uni-moded propagation. Note that the corrections become less effective as the frequency separation between the pair of transmitters increases though, in this particular case of co-located transmitters, they are still very good. Correlation falls off, as would be expected, with both frequency separation and also geographical separation.

It should be noted from Table 3 that a mean bearing correction, where the hourly averages of the bearing errors are subtracted, gives satisfactory results. This is quite a general result and has been found to apply with widely separated transmitters (up to 400 km) provided both transmissions are received by u.m.p.

### 5.3 D.F. Error Correction by Oblique Incidence Doppler Measurements

The successful outcome of the vertical incidence Doppler experiment described in Section 5.1 encouraged the setting-up of a further experiment in which an attempt is being made to relate the bearing error to the Doppler frequency shift on the received signal. This work, in cooperation with the Ionospheric Institute at Breisach, southern Germany, is so far only in its early stages but the results to date have been highly encouraging. This experiment can, at the moment, only be carried out when propagation is u.m.p. Uni-moded propagation conditions are identified by reference to oblique incidence ionograms obtained from a step-frequency pulse sounder co-located with the c.w. transmitter at Breisach. The simultaneous observations of Doppler shift and bearing error are reproduced in Fig. 7, from which it can be clearly seen that the two sets of measurements are very well correlated. Figure 8 is a correlellogram showing the relationship between bearing errors and Doppler shift and, even though there is no knowledge of the direction of the t.i.d. relative to the great circle path, the results cluster well around a smooth curve. A bearing error curve has been calculated from the Doppler shift on the assumption

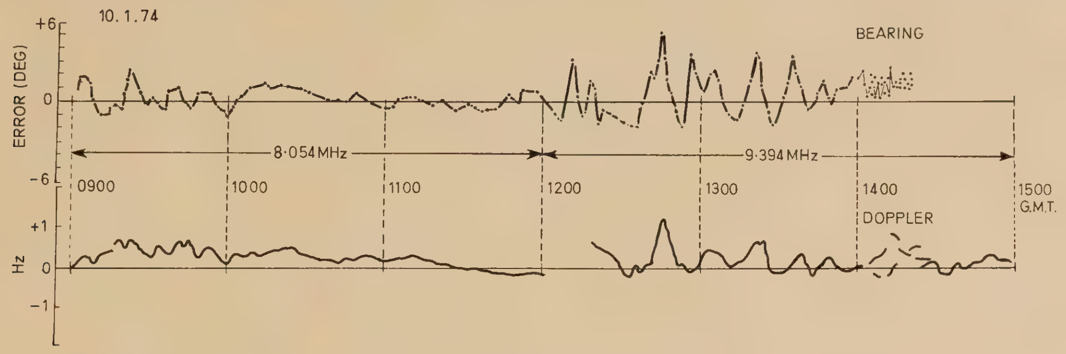



**Fig. 7.** Bearing error and Doppler frequency shifts recorded on transmissions from Breisach, West Germany.

that the t.i.d.s are travelling at right angles to the great circle path between transmitter and d.f. system. This curve is shown in Fig. 9 and demonstrates that worthwhile reduction of variance is obtained. This work will be continued to conclusion, the next stage being the setting up of a three-station Doppler system symmetrically disposed with respect to the h.f.d.f. system from which the direction of travel of the t.i.d.s may be deduced. This refinement is expected to produce a much better agreement between the bearing error curves and the correction curve deduced from the measurements of Doppler shift.

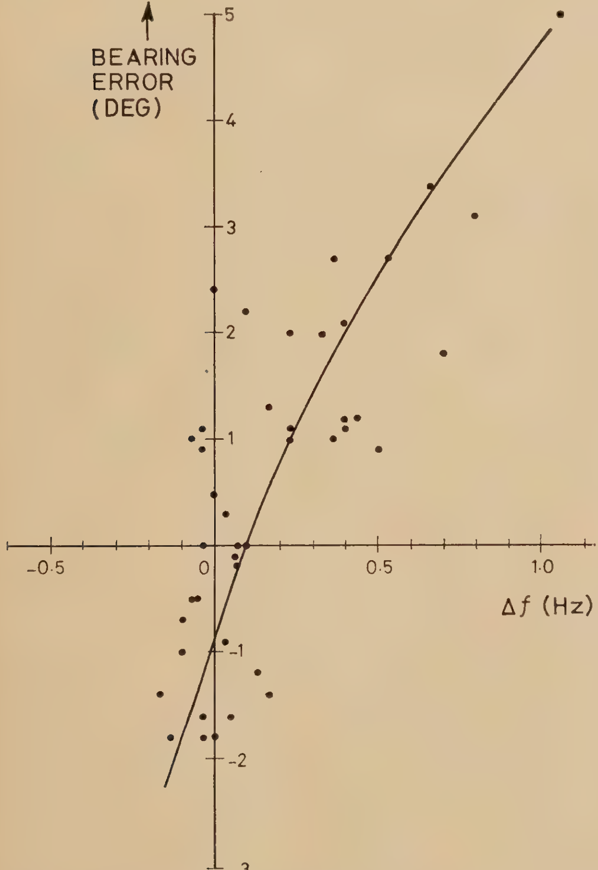



**Fig. 8.** Correlation curve relating bearing error and Doppler frequency shift. 10 January 1974, 1230 to 1400 G.M.T., t.i.d. active.

## 6 Conclusions

Given simple modes of propagation it is possible to reconstuct a geometrical representation of the t.i.d. from which meaningful bearing corrections can be deduced. Some direct experimental methods for bearing correction have been described in Section 5.

Looking ahead to an extension of these techniques there are, however, formidable difficulties to overcome.

(a) *Frequency stability.* Measurements so far have been made with highly stable transmitters (stability 1 part in $10^9$). This is necessary as the maximum Doppler shift on the oblique transmissions at 1000 km range is only of the order of 0·5 Hz. A technique for detecting the presence of t.i.d.s by Doppler measurement on unstable transmitters is being developed at Leicester but whether this would allow the reconstruction of the geometry of the t.i.d. is still an open question.

(b) *Multi-mode (single hop).* This case should be soluble provided mode resolution in azimuth can be achieved with the direction finding system. Mode resolution of the Doppler is already achievable in that, given different Doppler shifts for each mode, separate distinguishable traces appear on the Doppler records. A solution implies that the modes would have to be separated in both bearing and frequency shift and treated quite independently. A check of consistency would be available in that the bearings, after correction, should be the same regardless of the mode of propagation.

(c) *Multi-hop single mode and multi-mode.* This problem seems, with the current state of the art, to be intractable. A Doppler measurement would contain only path change information and it is likely that the Doppler trace would have a 'noise-like' form. Notionally at least it might be feasible to hypothesize t.i.d.s at each reflexion point and by 'hill climbing' techniques obtain a best fit solution for the $3n$ parameters required to define the t.i.d. for $n$ reflexion points, but little confidence is placed in this approach.

(d) *Multi-t.i.d.s.* It seems possible that there could, at times, be more than one t.i.d. affecting the ionosphere in the region of interest. This is probably the case when the Doppler traces are noise-like and do not correlate for a multi-station net. No attempt has been made to deal with these cases, and the remarks under (c) are equally applicable.

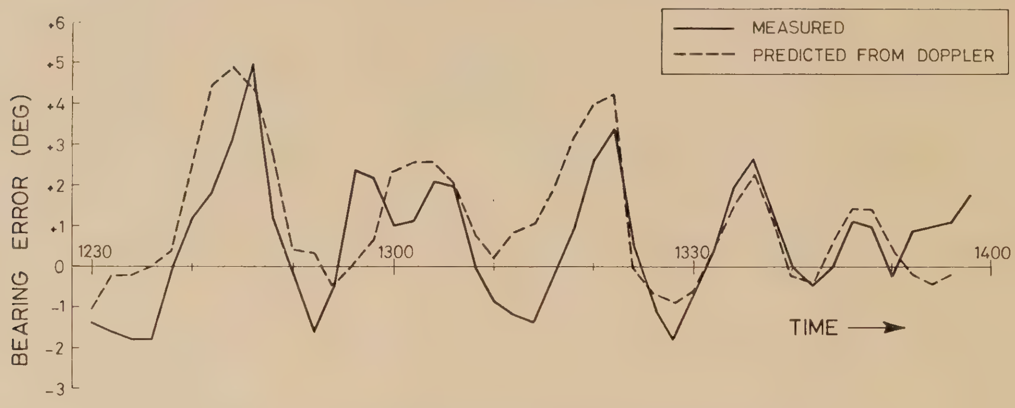



**Fig. 9.** Comparison of measured bearing errors with those calculated from the Doppler frequency shift on the received signal. 10 January 1974, 1230 to 1400 G.M.T., t.i.d. active.

It seems, therefore, that bearing correction for t.i.d.s is at present only feasible in the simplest cases. The improvement of d.f. variance is most likely to come from the selection of times when t.i.d. incidence is low and Doppler techniques will clearly be an important tool in identifying these periods.

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*Manuscript first received by the Institution on 11th June 1974 and in final form on 12th September 1974 (Paper No. 1624/Com. 105)*

# H.F. Heating Circuits and Techniques

## *Report of a Components and Circuits Group Colloquium held in London on 9th October 1974.*

Eight papers were given at this Colloquium and the ground which they covered between them could be roughly divided into three parts.

In the first area several of the authors specifically dealt with industrial engineering and commented that the problems of using h.f. heating were mainly associated with the installation of serviceable, reliable equipment in an environment that could be dirty, subject to vibration and generally one where maintenance would be carried out by people who regarded the whole apparatus as something of a mystery.

Illustrations of these problems were given very successfully by Mr. A. F. Watts of Vauxhall Motors and he added that a lot of the industrial engineering problems were concerned with union demarcation situations; for example, the fact that the electrician would be the man who would open the door but the plumber would be the man who was responsible for any water installation inside the equipment. The appeal therefore, was for better, more reliable equipment and two important points were made in discussion on this. The first was that the purchasers of industrial heating equipment were too price-conscious and would be concerned with saving £30–£50 in a total order of £10,000. In these circumstances it was difficult to engineer the best, most rugged equipment for the circumstances. The second point that was made was the real need for industry to employ trained production engineers. It was all too easy for industry to blame universities for producing the wrong sort of person for looking after equipment of this type, whereas in actual fact it was not easy to persuade industry to use trained production engineers.

The other, more technical aspect of industrial engineering that was discussed was the use of equipment in context and this is the area which at the moment occupies the majority of technical interest. Dr. J. Lawton of the Electricity Council Research Centre, gave a very interesting account of the use of h.f. heating in the paper and woollen industries, showing the type of problems that are being dealt with in this context.

The second group of papers was concerned with the developments of components and circuits for heating applications. These activities were, of course, of direct relevance to the IERE. Various aspects of this were discussed, notably in a paper by Messrs. R. Whittle and J. J. Behenna of STC, on the use of magnetically beamed triodes and a forward looking paper by Mr. G. Garrard of Texas Instruments on the future of semiconductors in h.f. heating. In this latter context it became obvious that transistors were not yet at the stage where they could compete in terms of £ per watt; in fact one estimate was made that even using 125 W transistors running at 1 MHz, the circuit costs for transistors along would be £350 per kW.

Circuit developments were discussed by Herr H. G. Matthes from AEG in Germany, who was concerned with the use of thyristor converters for induction heating and hardening and melting applications. Noise generation of these converters was discussed during question time, and it was mentioned that noise up to 19th harmonic was present, though h.f. noise tended to be damped out by capacitance resistance output networks.

The third area of interest lay in the problem of interference produced by h.f. heating circuits. Mr. A. S. McLachlan, from the Home Office, gave a paper on radio interference in which interesting statistics on the numbers of complaints received on interference, particularly with regard to colour television, were given, and the sources of the interference were analysed. In the year 1973, of the 52,270 complaints received, 636 were traced to industrial, scientific and medical causes, of which the majority, 313, were associated with plastic welders, 169 with dielectric handling and 30 with microwave ovens. Legislation in this country is not as tight as it is on the Continent and it was noted that for h.f. applications, international agreements allow only five frequency bands, including two in the microwave frequencies. In this country, eleven are allowed, although there are limits on the radiation allowed for six of these.

It was observed in discussion that the interference situation is dealt with on the basis of complaints and is therefore approached from a negative point of view, and there are no statutory obligations on the producers of the equipment. It is hoped that this situation will be changing in the future, particularly with regard to common EEC rules. A further consideration noted was that this type of interference which is radiated internally from the equipment, is of a different nature to mains-borne harmonic interference from thyristor switching, but is also an important aspect of the use of certain heating equipment.

In summary, the Colloquium illustrated that although the main problem in the use and development of h.f. heating for industrial applications had been overcome, development work is continuing in the field of components and circuits, and also in the use of heating in particular systems. Some of the challenges that were left with the meeting were given by Mr. H. Barber of Loughborough University of Technology. He felt that in the area of components and development, there was a great need to reduce the size of transformers and capacitors, to get rid of cooled water in the system if this was at all possible, and finally, to reduce considerably interference, as requirements in this area are going to become rapidly more stringent.

D. S. Campbell

'Power Sources for H.F. Heating and their Recent Development'
By W. D. Wilkinson (*Stanelco*)

'Requirements of H.F. Heating Equipment in the Industrial Environment'
By F. Watts (*Vauxhall Motors*)

'Drying Non-metallic Substances at High Frequencies'
By Dr. J. Lawton (*Electricity Council Research Centre*)

'Radio Interference from R.F. Heating Equipment'
By A. S. McLachlan (*Home Office, Directorate of Radio Technology*)

'Controlled R.F. Power Generation Using Magnetically Beamed Triodes'
By R. Whittle and J. J. Behenna (*STC*)

'Thyristor Convertors for Induction Heating and Hardening and Melting Applications'
By H. G. Matthes (*AEG*)

'The Future of Semiconductors in R.F. Heating'
By G. Garrard (*Texas Instruments*)

'Developments in R.F. Heating Techniques and their Influence on the Process Heating Field'
By H. Barber (*Loughborough University*)

UDC 621.373.54:621.3.049.77:744

# A digital generator for pattern drawing applications

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and

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SUMMARY

The generator may be used off-line or on-line to a computer. It is used principally for integrated-circuit mask generation but is also suitable for other precision pattern-drawing applications. The generator accepts commands to draw line segments, to outline or scan rectangles, and to replicate patterns in regular arrays (step-and-repeat). The output of the generator comprises $x$ and $y$ co-ordinate-direction pulses. The organization of the instrument allows the later addition of other pattern modules. The instrument is constructed from off-the-shelf TTL. The advantage of the generator, compared to earlier models, is the great economy it effects with respect to the bulk of input-data medium or to the density of data on the computer interface line.

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## 1 Introduction

The direct control of a pattern drawing peripheral by computer can be inconvenient on a number of counts. The bulk of output data to the peripheral often necessitates on-line control via a relatively busy interface. This reduces the availability of a small or slow central processing unit (c.p.u.) for other tasks. Off-line control is attractive particularly when the peripheral is geographically distant. The task can then be split into separate activities, namely the production of the data and the drawing of the pattern. However, without magnetic tape equipment both at the c.p.u. and at peripheral the bulk of data to be handled vies against direct off-line control. Pattern drawing is often confined to straight-line segments and arc-segments of circles and input for these entities can be generated by simple special-purpose hardware external to the c.p.u.

A vector generator which develops point-by-point output from the co-ordinates of line segments is an example of this philosophy. Such a system has previously been described for automatic drawing of integrated-circuit masks.[1] In this system the incremental co-ordinates of line segments are punched in paper tape by the computer. The vector generator and plotting table are off-line and remote from the computer. Even so, the bulk of paper tape remains a problem for the more complex masks. This arises out of the large number of line segments required to scan a rectangular area and also because of the need to re-present input data for regular pattern replication (step-and-repeat).

A solution is to perform more complex pattern-generation functions in the peripheral processor.[2,3] If this concept is taken too far, the complexity of the peripheral processor approaches that of the main c.p.u. There may then be a case for using a dedicated micro-computer as the peripheral processor. However, the elimination of the main c.p.u. is not really viable since some high-level language is needed for almost all pattern-drawing applications and this language cannot be coded into a micro-computer of limited memory capacity and restricted order code. The use of a micro-computer simply as a peripheral processor is a topic worthy of investigation but is not considered here. Critical appraisals of the trade-offs between software and hardware data processing for peripheral channels have been given by Schutz[4] and by Loi.[3] This paper describes a peripheral processor which performs more complex functions than a line generator but which is nevertheless much simpler and cheaper than a programmable micro-computer.

## 2 Function of the Generator

The input data to the generator are in the form of control characters and incremental co-ordinates. The presently implemented data lines are given in Table 1.

For example, referring to the first entry in this table, the control character N followed by the data $X$ and $Y$ instructs the processor to move position (without the drawing of a vector) from the current position to the position with co-ordinates incremented by $X$ and $Y$.

```
S
S
N 0 25
R 425 25
N-425 25
S
F 25 50 50 100 50 25
N 25-175
A 3
N-450 175
S
R 50 50
N-25 0
R 25 25
N 25-75
A 6
N 50-250
A 3
N-1500 350
A 2
Q
```

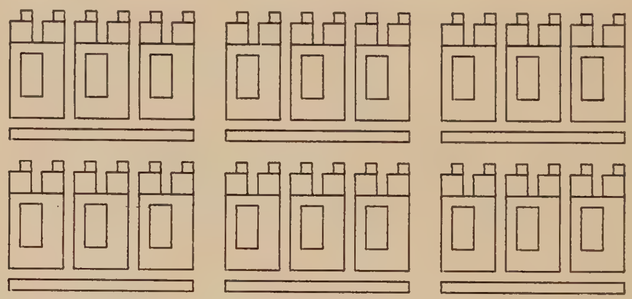

**Fig. 3.** Nested replication in OUTLINE mode.

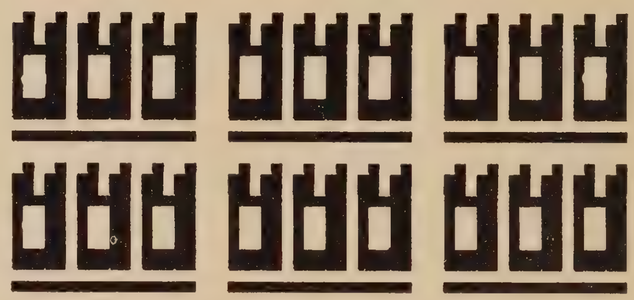

**Fig. 4.** Pattern of Fig. 3 in SCAN mode.

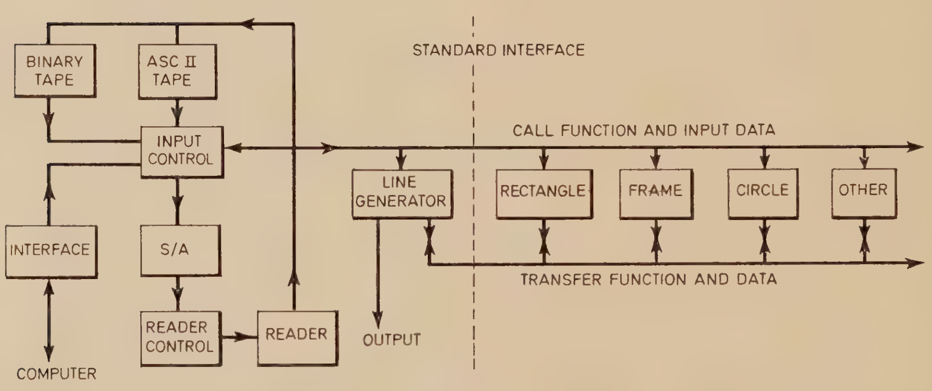


**Fig. 5.** Block diagram of the processor.

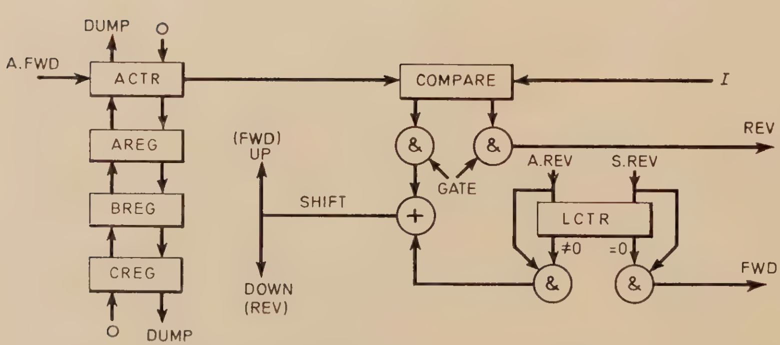


**Fig. 6.** Block diagram of the replication module.

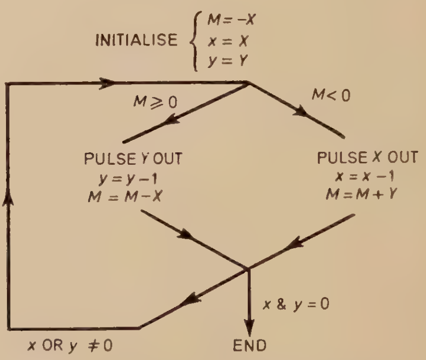


**Fig. 7.** Flow chart of algorithm for best straight line through a digital mesh.

**Table 1.** Data lines

| Data line | | |
|---|---|---|
| Control | Data | Action |
| N | *X Y* | nul line |
| C | *X Y* | line |
| R | *X Y* | rectangle, sides *X* and *Y* |
| F | *X*1 *Y*1 etc. | frame, see Fig. 1 |
| S | Absent | start mark for replication |
| A | *I* | end mark, replicate *I* times |
| Q | Absent | stop |

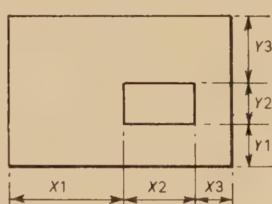


**Fig. 1.** Frame pattern produced by the control characteristic F

The second entry with control character C similarly instructs the processor except that the vector is drawn. In the case of the character R the processor produces all the data necessary to draw a rectangle of sides *X* and *Y* parallel to the co-ordinate axes. The more complex *frame* pattern shown in Fig. 1 is produced by the control character F. The function of the characters S and A will be discussed later. There is no restriction on the gradients of vectors drawn by the control character C, and Fig. 2 shows the vectors drawn by the related data list.

In one mode (OUTLINE) of the generator, only the perimeters of rectangles and frames are drawn. In the other mode (SCAN) the areas of rectangles and frames are scanned by sequences of lines parallel to the longer edges of the entities. The separation *D* of the scan lines is set as an even four-bit binary number on three panel switches and each corner of the rectangle (or frame) is automatically inset by $(\frac{1}{2}D, \frac{1}{2}D)$. This is to accommodate various line widths of the drawing device. The control character S is used to indicate that the following data is to be replicated and the character A to close a replication loop (step-and-repeat). The replication index $I < 16$. Replication loops can be nested to a depth of three. The replication is effected with a reversible tape reader under control of the generator. Figure 3 is an illustration of nested replication in OUTLINE mode and Fig. 4 the same pattern in SCAN mode. The input data for this pattern are also shown in the Figure. The input data for this pattern are normally in ASC II code freely formatted with non-significant zeros and plus signs suppressed. Data for simple patterns can be produced directly on a teletype and computer-produced data for more complex patterns can be printed on a teletype. Binary data on paper tape (two frames to a co-ordinate) can also be used with some economy of tape length. In another input mode, binary data (16-bit) may be accepted on-line from a c.p.u. although, for the obvious reason, replication is then inhibited.

## 3 Construction of the Generator

A modular form (see next Section) of construction is used. All logic is implemented in standard range TTL including a number of m.s.i. functions. The generator comprises thirty 20 cm × 12·7 cm (8 in × 5 in) printed-circuit boards, exclusive of supplies, with an average of about ten TTL packages to a board. It has been operating reliably for about 18 months and has been used in conjunction with a digital (stepping-motor driven) plotting table and also with a precision c.r.t. display.

## 4 Modular Form of the Generator

Figure 5 is a block diagram description of the processor. At the lowest hierarchical level is the line generator from which all output occurs. The rectangle generator is at the next highest hierarchical level and uses the line generator for each of its perimeter or scan lines. At the highest level is the frame generator and the frame pattern is formed by four rectangles. The circle generator has been designed and simulated in a computer (simulations of hardware circular-arc generation have also been described by Hughes and Hawkins[5]). Our proposed circle generator is on two levels, a circle outline module and a circle radius control module which uses the former module to scan a disk or annulus as a series of concentric circles. A standard interface is used between the line generator and the function generators and this allows the later addition of further function modules. The module S/A implements the replication facility. Some principles and features of the design of various modules are discussed in the following Sections.

## 5 The Replication Module (S/A)

Figure 6 is a simplified block diagram of the module. ACTR, AREG, BREG and CREG form a push-down store for holding nested replication indices (*I*). On push-up or push-down the end register (top or bottom) of the stack is cleared. The signals FWD and REV control the direction of motion of the tape reader. Initially all registers are

```
C 0 600
N 100 0
C-100-600
C 200 600
N 100 0
C-300-600
C 400 6900
N 100 0
C-500-600
C 600 600
N 0-100
C-600-500
C 600 400
N 0-100
C-600-300
C 600 200
N 0-100
C-600-100
C 600 0
N-600 0
Q
```

**Fig. 2.** Vectors drawn by data list.

clear. As the tape is read all function commands are obeyed and S characters ignored. An A character increments ACTR (A.FWD) and the following index $I$ is compared with ACTR. The FALSE comparison reverses the reader (REV). The same A is re-read and increments LCTR. In reverse read only S and A characters are sought and each S decrements LCTR which sets FWD when empty. The data in the loop are thus repeated until the ACTR-I comparison is TRUE. Forward data reading then continues and an UP-shift dumps ACTR. When the loop is nested in another, two A's in the reverse read of the outer loop increment LCTR twice. The second A shifts the stack down (since LCTR $\neq 0$ and REV) thus saving the outer loop count in AREG. The reader continues in reverse until two S characters empty LCTR. The forward read to the first A brings up the inner index $I$ again and ACTR is available to the inner loop which is thus repeated again $I$ times. The TRUE comparison then shifts the outer-loop count up from AREG to ACTR and reading of the outer loop continues. Each time the inner loop A is encountered, the stack is pushed down and the inner loop is replicated. This system is capable of handling any number of non-intersecting inner loops. Nesting to greater depths is accommodated by pushing the stack down further into BREG, etc.

## 6 The Line Generator

Co-ordinate sign information is output separately and the line generator is presented with co-ordinate magnitudes. Generation of lines parallel to a co-ordinate axis is straightforward and only the case of a gradient line is discussed. Figure 7 gives the flow chart of an algorithm which produces a good approximation to the best straight line through a digital mesh. The incremental co-ordinates are $X$ and $Y$ and $M$ is the contents of a special register. The contents of co-ordinate counters are $x$ and $y$. Table 2 illustrates the sequence of operation for the line (10, 3). The practical implementation uses a slight modification of this algorithm for reasons which are unimportant here. Re-circulating shift registers are used for $-$X (*two's* complement), Y and M (negative values in *two's* complement). Serial addition of either $-$X or Y to M (controlled by sign bit of M) is thus simple and economic to implement.

## 7 The Rectangle Generator

In OUTLINE mode this generator causes the line generator to process C($X$, 0), C(0, $Y$), C($-X$, 0), C(0, $-Y$), and N($X$, $Y$) as shown in Fig. 8. In SCAN mode, illustrated in Fig. 9, the scan separation $D$ is preset. The line generator calls required are (for $X > Y$); N($\frac{1}{2}D$, $\frac{1}{2}D$), C($X-D$, 0), C(0, $D$), C($-X+D$, 0), C(0, $D$), and so on and concluding with N($\frac{1}{2}D$, $\frac{1}{2}D$). When $Y$ is not precisely divisible by $D$, the final vertical line is necessarily shorter than D. Also, when the scan finishes at the top left-hand side an extra N-line is needed to get to the correct finish point. A simplified diagram of the rectangle generator is given in Fig. 10. Only the more complex SCAN mode is discussed. The data are input serially via G2 and G8 ($X$) or G4 and G8 ($Y$). Re-circulation via G1 and G3 allows serial addition of $-D$ to form ($X-D$) and ($Y-D$). A single shift of $D$ is used to form N($\frac{1}{2}D$, $\frac{1}{2}D$) which is output via G7. An initial comparison of $X$ and $Y$ causes G5 or G6 to be exclusively selected on subsequent occasions for the longer-edge line scan. Sign control is accomplished separately. The connecting segments of the scan line (see Fig. 9) are obtained by re-entry and output of D via G7. Simultaneously $-$D is added (via G9 or G10) to the shorter-edge co-ordinate as it is re-circulated. The other co-ordinate is unchanged by re-circulation via G1 or G3. When the short edge falls below $D$, this final value is output instead of $D$.

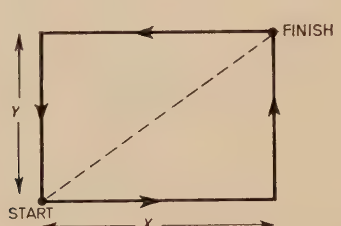


**Fig. 8.** Rectangle generation in OUTLINE mode.

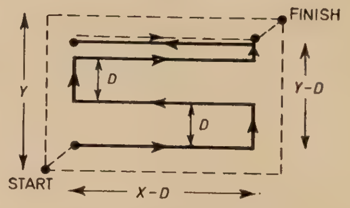


**Fig. 9.** Rectangle generation in SCAN mode.

## 8 Conclusion

A peripheral processor for drawing rectilinear patterns particularly suited to integrated-circuit and printed circuit board mask production has been described. The input data required by the processor are at the relatively high level of line, rectangle and frame data, and are expressed in simple format. The algorithms embodied in the logic of the processor require only elementary

**Table 2.** Sequence of operation for line (10, 3)

| $M$ | $X$ Pulse | $Y$ Pulse | $x$ | $y$ | Add to $M$ |
|---|---|---|---|---|---|
| −10 | 1 | 0 | 9 | 3 | 3 |
| −7 | 1 | 0 | 8 | 3 | 3 |
| −4 | 1 | 0 | 7 | 3 | 3 |
| −1 | 1 | 0 | 6 | 3 | 3 |
| 2 | 0 | 1 | 6 | 2 | −10 |
| −8 | 1 | 0 | 5 | 2 | 3 |
| −5 | 1 | 0 | 4 | 2 | 3 |
| −2 | 1 | 0 | 3 | 2 | 3 |
| 1 | 0 | 1 | 3 | 1 | −10 |
| −9 | 1 | 0 | 2 | 1 | 3 |
| −6 | 1 | 0 | 1 | 1 | 3 |
| −3 | 1 | 0 | 0 | 1 | 3 |
| 0 | 0 | 1 | 0 | 0 | End |

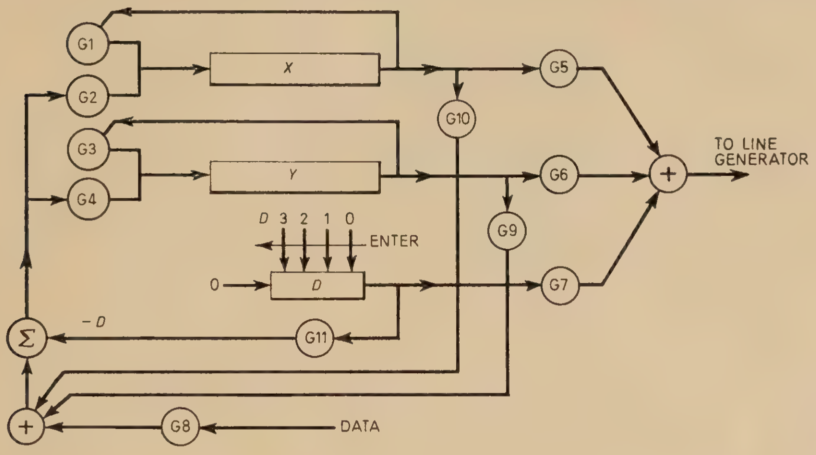


**Fig. 10.** Diagram of the rectangle generator.

arithmetic operations, with the result that the processor is relatively simple in design and construction compared to a c.p.u. The maximum output speed of the processor is limited by the TTL logic used in its construction and the serial arithmetic employed. However, outputs at a rate of 100,000 drive pulses per second have been demonstrated, but in practice the characteristics of the plotting or display device which the processor drives require lower drive rates. A substantial speed increase could be achieved if necessary by employing parallel arithmetic particularly in the line generator module.

## 9 Acknowledgment

The support of the Science Research Council is gratefully acknowledged.

## 10 References

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*Manuscript first received by the Institution on 8th April 1974 and in final form on 5th June 1974. (Paper No. 1625/Comp. 154)*

# Contributors to this issue*

**Dr. W. C. Bain** received his degree in physics at Aberdeen University in 1948 following four years service as a radar officer in REME. He remained at the University to pursue research into v.l.f. radio wave propagation and its relation to the D region of the ionosphere, receiving his Ph.D. degree in 1951. He then moved to the Radio Research Station, Slough (now the Appleton Laboratory) and carried out research on various topics, notably h.f. direction-finding, ionospheric forward scatter, and laser investigations of the upper atmosphere. He became a Senior Principal Scientific Officer in 1964 and is in charge of a division engaged on ionospheric research at the Laboratory.

**Dr. Henry Rishbeth** received his B.A. degree in mathematics and physics at the University of Cambridge in 1954. He undertook research in radio astronomy at the Radiophysics Laboratory of the University of Sydney, from 1955 to 1957, and ionospheric physics at the Cavendish Laboratory, Cambridge, from 1957 to 1960. He then joined the staff of the Radio Research Station, Ditton Park, Slough (now the Appleton Laboratory) and has remained there since, apart from a $2\frac{1}{2}$-year period spent mainly at the (then) National Bureau of Standards, Boulder, Colorado. He is currently a Senior Principal Scientific Officer, in charge of an ionospheric incoherent scatter experiment and also carrying out theoretical ionospheric research. He received the degrees of Ph.D. in 1960 and Sc.D. in 1971 from the University of Cambridge.

**Mr. F. E. Cook** received the B.Sc. degree in physics from the University of Adelaide in 1950. While operating the ionospheric station at Mount Stromlo near Canberra and assisting with solar observations there, he began a study of solar-terrestrial relationships and developed techniques for predicting geomagnetic and ionospheric disturbances. In 1961 he moved to Sydney where he is in charge of the Warning Section of the Australian Ionospheric Prediction Service of the Department of Science.

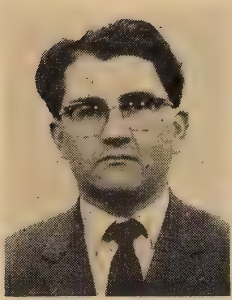
**Mr. Clarrie McCue** graduated from the University of Sydney in 1950 with an honours B.Sc. in physics. He received an M.Sc. from Sydney in 1953 for research performed with the Ionospheric Prediction Service on geomagnetic–ionospheric relationships. He spent 1952–53 as an attached Scientific Officer at the Radio Research Station, Slough, working on problems of ionospheric radio wave propagation. On return to Australia he worked at the Weapons Research Establishment on a variety of h.f. and v.h.f. radio problems till late 1967, apart from two years when he lectured in physics at the Royal Military College, Duntroon. Since 1967 he has been Assistant Secretary in charge of the IPS Branch of the Australian Government Department of Science where he is still able to find some time for research related to ionospheric prediction.

**Mr. L. W. Barclay, B.Sc.** (Fellow 1967, Member 1960, Graduate 1955) has worked in the field of ionospheric radio wave propagation since 1956: he is currently chief of the Ionospheric Propagation Section of the Marconi Research Laboratories. He started his professional career in 1950 with E. K. Cole Limited, Southend-on-Sea, initially as a student apprentice and later working in the television research laboratory. During this period he obtained a London University external degree in physics and mathematics as a result of part-time studies at Southend Municipal College and he subsequently took Higher National Certificate Examinations with endorsements to gain exemption from the Institution's Graduateship Examination.

In 1956 Mr. Barclay joined the Royal Society's Antarctic expedition as an Ionospheric Physicist, and before and during the International Geophysical Year he spent some two years at Halley Bay setting up and operating an ionospheric sounding station. He returned to the Radio Research Station at Slough to analyse the results and prepare a report on the work and he was awarded a Polar Medal for contribution to knowledge of the Antarctic. In 1960 Mr. Barclay joined the Propagation Field Studies Section of the Research Division of Marconi Company and established a prediction and consultation service for m.f. and h.f. In 1966, following re-organization of the Research Division, he was appointed to his present position.

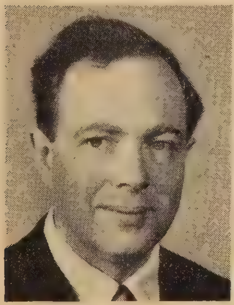
For a number of years Mr. Barclay has been an active member of the British Delegation to CCIR Study Groups concerned with ionospheric propagation. He has written numerous papers in scientific and technical journals; these include a paper on 'Reception of BBC television sound transmissions on 41·5 Mc/s at Halley Bay, Antarctica' which was published in the Institution's Journal in January 1961. Mr. Barclay has been a member of the IERE Papers Committee since 1968 and he has also served on the Communications Group Committee for several years. As Guest Editor of this Special Issue he has been largely responsible for obtaining and assessing the papers.

* See also pages 46 and 81.



**Dr. B. Burgess** joined the Radio Department at the Royal Aircraft Establishment, Farnborough, in 1954, after being awarded a Ph.D. at the University of Wales. Initially he worked on propagation and aerial research associated with various aircraft and missile systems, and he later joined the Navigation Division where he was concerned with the radio propagation effects associated with the use of very low frequencies for radio navigation systems. He has published a number of papers on this topic at various international symposia and also in scientific journals. Since 1971 he has been working in the field of aircraft radio communications and is now Head of the Communications Division of the Radio and Navigation Department at RAE.

**Dr. Tudor B. Jones** graduated in physics at the University College of Swansea in 1956 and was awarded the Ph.D. degree of the University of Wales in 1959 for research in ionospheric physics. After a period at the University College of Wales, Aberystwyth, he was appointed Lecturer (1962) and Senior Lecturer (1969) in Physics at the University of Leicester. In 1971 he was awarded a Senior Research Associateship by the National Academy of Sciences and spent a year at the Boulder Laboratories of the National Oceanic and Atmospheric Administration (then part of the National Bureau of Standards). Dr. Jones has published extensively in the fields of ionospheric physics and radio science and is a consultant to a number of Government Laboratories active in these areas. Currently he is a member of the British National Committee of the Royal Society for Radio Science.



**Mr. P. A. Bradley** received the B.Sc. degree in electrical engineering from Manchester University in 1956. He then joined the DSIR Radio Research Station at Slough (now the Appleton Laboratory of the Science Research Council) where he is currently employed as a Principal Scientific Officer. His initial work was the study of atmospheric radio noise and this involved periods in Singapore and Ibadan, Nigeria. He was awarded the M.Sc. degree from the University of Singapore in 1971 for research on the comparison of energy spectra of atmospherics radiated by lightning discharges in tropical and temperate regions. Since 1963 he has been concerned principally with problems of radio wave investigations aimed at improving prediction methods. He is a United Kingdom member of Study Groups of the CCIR concerned with Ionospheric Propagation and with Sound Broadcasting, and has served as a delegate to international CCIR meetings. He has published a number of papers on atmospheric noise and ionospheric propagation.

**Mr. J. S. B. Reynolds** graduated from Manchester University in 1949 and worked for 3 years with Ferranti Limited at Moston on guided missile development before joining the Scientific Civil Service in 1952. For the next few years he was concerned with research and design of microwave aerials and receivers before specializing in high frequency direction finding. For the last 10 years he has been actively engaged in the design of both narrow aperture and wide aperture direction finders at the Government Communications Headquarters. Latterly he has been investigating inaccuracies due to ionospheric perturbations and systematic tilts.

**Mr. D. O. Crawford** was at the University of Southampton from 1970–1972, studying first for the M.Sc. degree and subsequently working on computer aided design. He is now with Zirkon Electronics Limited, Biggleswade, where he is concerned with switched power supply design. Before going to the University, Mr. Crawford served eleven years with REME servicing communications equipment. He subsequently worked with a geophysical exploration company overseas for six years and in 1964 he joined Pye Dynamics Limited, as a designer of test and control equipment. He later spent nearly two years designing digital equipment on a contract basis for Plessey and ICL.

**Mr. R. J. Hale** has been with the Electronics Department of Southampton University for the past five years and he is now a senior experimental officer in the computer aided design section. He graduated with a B.Sc. degree in electrical engineering from University College, London, and he then worked for several years with the British Post Office as an Executive Engineer.

**Professor K. G. Nichols** (Fellow 1967, Member 1960) was appointed to a Chair in electronics at the University of Southampton in April 1974. He joined the Department of Electronics as a lecturer in 1961 and he was appointed to a Readership in 1970. Professor Nichols has been a member of the Council of the Institution since 1973 and he served on the Education and Training Committee for several years as well as on the organizing committees for national and regional conferences. He recently spent a year as IBM Fellow at the Hursley Park Research Laboratories. He has contributed numerous papers to this and other journals, and is author or joint author of three books.

# IERE News and Commentary

## Index for 1974

The Index to Volume 44 of *The Radio and Electronic Engineer* will be published in March in its customary format. In order to make some economies in the Institution's use of paper, copies will only be sent automatically to libraries and other organizations which subscribe to the *Journal*. Members of the Institution who wish to obtain a copy of the Index either for including in bound volumes or for reference purposes may obtain a copy free of charge on application to the Publications Department, Institution of Electronic and Radio Engineers, 8–9 Bedford Square, London WC1B 3RG. As a limited number only will be printed it would be helpful if such requests are made as soon as possible. Indexes will be incorporated in the bound volumes supplied by the Institution.

## Abstracts x $10^6$

The statistically minded will note with interest that, in the mid-October issue, there appeared the millionth abstract to be published in *Physics Abstracts* since 1898. It related to a paper on cryogenic fluid mechanics, one of the many subjects which has had that exponential growth which has been a characteristic of the output of literature on physics. INSPEC, who publish *Physics Abstracts*, stated that the first 100 000 abstracts took 37 years to accumulate, the second 100 000 was reached in the following 19 years, and subsequent 100 000 abstracts were reached in 7 years, 4 years and 3 years respectively. At present growth is rather more linear, about 100 000 being produced every 14 months. In this last connexion Professor Gosling's Inaugural Address in the December 1974 issue makes a very relevant comment.

The IERE is associated with INSPEC in the publication of the companion *Electrical and Electronics Abstracts*. Here the rate is somewhat less rapid, though still impressive, the half millionth electrical abstract appearing in September 1973; this related to a paper in a German publication on high-voltage switch gear.

The third abstracts journal, *Computer and Control Abstracts*, recently reached its 100th issue concurrently with the 1000th issue of Physics Abstracts, and the total number of abstracts published is in the region of 100 000. Altogether, up to September 1974 no fewer than 1683786 have been published by the three journals.

## Special Issue on Ionospheric Radio Wave Propagation

Single copies of this combined January–February 1975 Special Issue may be purchased from the Institution's Publications Sales Department at a charge of £2·50 each post paid.

## Membership Committee Meets Outside London

The Institution's Membership Committee created an interesting precedent recently when one of its normal monthly meetings was held at Crawley Court, near Winchester, the engineering headquarters of the Independent Broadcasting Authority. According to Institution records, this is the first time on which a formal meeting of a standing committee of the Council has been held away from Bedford Square, and the facilities on this occasion were arranged by courtesy of Mr. R. C. Hills (Fellow), a member of the Council and of the Membership Committee, who is Chief Engineer (Transmitters) with the IBA.

During the afternoon members of the Committee were able to see some of the work of the technical sections of the Engineering Division and it was generally agreed that this innovation in Committee work was highly productive, informative and stimulating.

## *Electronics Information and Planning*

A monthly journal is now published by the Information Planning and Analysis Group (IPAG) of the Electronics Commission of India, which is intended to serve government, industry and users by providing information about the country's electronics industry.

Typical articles describe the current status and problems of particular branches of the industry or present reports of planning panels set up to investigate, for instance, components development and manufacture. Broader articles survey such subjects as world-wide developments in navigational aids. Another article discusses potential geographical locations for setting up electronics industries in India.

*Electronics Information and Planning* may be obtained on annual subscription outside India at a rate of Rs. 120 or $15 from: Electronics Commission HQ, 8th Floor, Air India Building, Nariman Point, Bombay 400001, India.

## Electronic Components Board

With effect from 1st January 1975, Mr. Henry J. Kroch, O.B.E., Managing Director of AB Electronic Components Limited, takes over as Chairman of the Electronic Components Board in succession to Mr. Alfred Deutsch, C.B.E., who has completed his two-year term of office. Mr. Jack Akerman, Managing Director of Mullard Limited, has been elected Vice-Chairman of the Board.

## The Late Sir Frank Wood

At the recent Memorial Service to Sir Frank Wood, K.B.E., C.B., at St. Clement Danes, Strand, London, Earl Mountbatten of Burma was represented by Mr. Graham D. Clifford, Director of the IERE. Sir Frank was from 1969 to 1974 Deputy Secretary at the Ministry of Posts and Telecommunications. He previously held appointments at the Ministry of Aviation, the Ministry of Defence, and the Civil Aviation Department of the Board of Trade.

## IEEE Members Reject Constitutional Changes

Two proposed amendments to the constitution of the Institute of Electrical and Electronics Engineers Inc., one to create a paid President and the other to reduce the number of signatures required to nominate Institute officers, have both been defeated by a vote of the membership. The proposals had been placed on the ballot by petition, and passage would have required approval by at least two-thirds of those voting.

The proposal to have an elected paid President, serving a three-year term, was rejected by a greater than two-to-one margin. Of the more than 43 000 votes cast, 70% were against the change. Currently the IEEE President serves a one-year term and receives no salary.

The suggested amendment reducing the number of signatures required to place a name on the ballot from 2% to ⅓% was defeated by a vote of 24 001 against and 18 592 in favour.

The IEEE's Board of Directors had opposed both propositions.

## Joint IEE–IERE Conference Publications

Members of the IERE may purchase single copies at reduced rates of the following volumes of papers read at conferences for which the Institution was a co-sponsor:

**Circuit Theory and Design,** July 1974 (IEE Conference Publication 116) £9·80 (normal price £14·70)

**Control Aspects of New Forms of Guided Land Transport,** August 1974 (IEE Conference Publication 117) £6 (normal price £9)

**Gas Discharges,** September 1974 (IEE Conference Publication 118) £12·20 (normal price £18·30)

**Power Electronics and Power Semiconductors and Their Applications,** December 1974 (IEE Conference Publication 123) £6·70 (normal price £10·20)

Orders from members who wish to take advantage of these special rates should be placed through the IERE Publications Department, 9 Bedford Square, London WC1B 3RG.

# CEI News

## The 20th Graham Clark Lecture—Further Details

The Graham Clark Lecture, to be given by Sir Frederick Catherwood at the Institution of Civil Engineers on Wednesday, 26th February 1975, will be on 'The Diseconomies of Size and the High Cost of Discontinuity'. In it he will cover the lack of evidence for economies of scale in mergers; problems of running conglomerate companies; problems of communication in very large bodies—the dinosaur syndrome; economies of specialization, of long runs, of distribution; methods of obtaining economies in small organizations; the economies of joint ventures, joint marketing, outside specialist help; the legal bias towards merger and against joint-venture; the vulnerability of large organizations to industrial action; and the costs of discontinuity in large organizations.

Sir Frederick will start his lecture at 6.00 p.m. Tickets will be obtainable near the date from CEI or from any of its member institutions.

## Registration Statistics

The Engineers' Registration Board has issued an analysis of the registration figures for Technician Engineers and Technicians at 30th September 1974. A total of 35 974 Technician Engineers and 12 315 Technicians were on the registers; the largest numbers given in the analysis were for T.Eng. registrations by the Institution of Electrical and Electronics Technician Engineers (8330) while the Society of Electronic and Radio Technicians (SERT) registered 1450 for T.Eng. and 3331 Technicians; the latter figure is the highest for any of the 26 institutions who register Technicians.

The IERE registers Associate Members as Technician Engineers and at 30th September there were 475; this figure has now risen to 536.

## Detail Design Conference

A conference on Detail Design, organized by the Institution of Mechanical Engineers and sponsored by CEI as part of the programme 'Design in the Mid-70s', will take place at the University of Keele on 3rd–4th April 1975. The Mechanical Engineering Little Neddy's Industrial Review to 1977, which emphasizes the importance of superior design and fitness for purpose in goods for export, says 'The main requirement is improvement in the quality of detailed design input . . .'.

The Conference will discuss the diversity of Detail Design requirements for, among others, domestic refrigerators, rail vehicles, goliath-cranes, service equipment for the armed forces, aircraft, gas turbines, the place of standardization in Detail Design and many other aspects of this important topic. Component design for automated assembly will also be dealt with. Sixteen papers are to be presented and discussed.

Detailed information and registration forms are obtainable from the Conference Department, Institution of Mechanical Engineers, 1 Birdcage Walk, London SW1H 9JJ. Telephone: 01-839 1211.

## Association of Retired Engineers

Members of the Institution who have retired to the Sussex area may like to know of the existence of the Association of Retired Engineers. This organization was founded in 1951 and its objects are to enable retired engineers to meet and retain their interests in the profession by, for instance, visits to local engineering works and other places of general interest. Informal social gatherings take place regularly in Worthing and Brighton, and as well as helping members to find interesting and useful occupations, practical assistance is given where possible to sick and infirm members.

Eligibility for membership extends to retired men living in Worthing or district who are, or were on retirement, corporate members of a Chartered Engineering Institution. Those of normal retiring age who are still partly employed are accepted as retired. There is a small entrance fee and annual subscription. Further information may be obtained from the Honorary Secretary, Mr. Eric L. Higgins, F.R.T.P.I., C.Eng., M.I.Mun.E., 111 Goring Road, Worthing, Sussex (Tel. Worthing 43068).

# Statistics of the Electronics Industry

The eighth edition of the 'Annual Statistical Survey of the Electronics Industry'† published by the Electronics Economic Development Committee, charts the industry's progress in 1973 and reveals that total sales reached over £2600M—a 12% increase over 1972. After a brief pause in 1971/72 the industry's expansion has resumed but at a slower rate than before. Nevertheless, it is clear that output has more than doubled since 1968.

The survey shows that the electronics industry's renewed growth was led by the components sector with an 18% growth rate and the consumer goods sector with a 16% rate. This largely stemmed from the demand for colour television which peaked in November 1973; over 2·1 M sets, worth £285M, were produced in 1973—a 43% increase over the previous year. Also in 1973 sales of electronic calculators doubled to reach £16M, although the home demand was met largely by imports. Sales of computers in 1973 were worth £350M, of which 45% were for export. The Post Office's programme of expansion and modernization helped telecommunications sales to reach over £400M—equal to a 10% growth rate over 1972. The capital equipment and instruments sectors each maintained a lower growth rate of about 7% with instrument sales reaching £400M—of which 44% were exported—and with capital equipment sales of £380M, of which £110M were for export.

Intake of orders for radio, radar and other electronic capital equipment, from home and abroad, was rising in 1972, throughout 1973 and subsequently. Overseas competitors have faced similar supply difficulties and UK manufacturers have been further aided by the effective devaluation of sterling. This has been particularly true of marine equipment. Much communications equipment has been fitted to oil drilling rigs and there has been strong demand at home and abroad for communication and navigation systems for vessels of all classes, and for closed circuit television. Compared with 1972, direct exports of marine communications equipment rose 18% and radar and navigational aids 13%. Major customers were a number of European countries, the USA and Japan.

Demand for mobile communications equipment from commercial users and public authorities has been buoyant and imports have continued to flow in. On the other hand, the *Clansman* mobile system is proving as popular abroad as at home.

Suppliers of public broadcasting equipment too had a good year. The main impetus was, and still is, demand for colour television networks. The principal customers were Italy, South Africa, Oman and other Arabian Gulf states, Australia, Egypt and Korea. At home, the BBC continued to improve their television network and highly automated studio and transmission equipment was supplied to the new local radio stations. Imports fell by 63%.

The average quarterly sales of closed circuit television were 32% higher in 1973 compared with the latter half of 1972. Direct exports rose 41% over the previous year but imports, especially of less sophisticated equipment, more than doubled, the main sources being the Netherlands and Japan.

There was a noticeable expansion of trade in electro-medical and especially medical X-ray equipment.

While the industry re-established its pattern of growth in 1973, the home market underwent enormous expansion. The resulting trade deficit was £268 M, almost a four-fold deterioration over 1972. The largest deficits were in consumer goods (£219 M), active components (£68 M) and computers (£52 M). None of the sectors with positive trade balances improved their position although the instruments sector exported a slightly higher proportion of total sales—44%.

The industry's growth in 1973 reversed employment trends and the workforce increased by 4% to 533 000. The largest increases were of the number of part-time female workers in the components and consumer goods sectors. Only the computer sector continued to reduce its labour force with a drop of 10%.

The total work forces for the various sectors were 137 000 in components, 105 000 in instruments, 93 000 in telecommunication equipment, 80 000 in capital equipment, 70 000 in consumer goods and 47 000 in computers.

There continues to be a high concentration of the electronics industry in the South-East of England. Fifty per cent of the industry's work force is in the South-East, with a relatively low concentration in the industrial regions of the Midlands and North. The industry outside London and the South-East has been spread around the peripheral regions of the country. The only sector with any major concentration in the Midlands and North-West is the telecommunications sector with plants around Nottingham, Liverpool and Coventry. As yet only 4% of the electronics industry is located in Wales; half of these are in the components sector. A higher percentage of the electronics industry than the average for manufacturing industry as a whole is located in Scotland.

An analysis of the occupational structure of the electronics industry shows that compared with all engineering industries, scientists and engineers are 5% of the work force as against 3%—representing about a third of all scientists and engineers in engineering industries. Nearly half the women employed in the engineering industries of the country as scientists and engineers work in electronics—220 out of 470—and a similar proportion applies for draughtswomen and other technicians.

Average earnings in the industry for male manual workers were £37·30 per week—below the average for manufacturing industries generally (£39·90). Average wages earned by female manual workers were in line with the average for manufacturing industries at £20·90 per week. Non-manual workers in the industry earned well above the average for manufacturing on account of the larger proportion of qualified employees in technical, managerial and administrative posts in the electronics industry.

From a safety point of view the electronics industry has had virtually no fatalities over the past four years but, though not especially high, the incidence of severe injuries has not shown the steady fall that manufacturing industries as a whole have achieved. The incidence per 100 000 employees was 200, 230, 240 and 220 in the past four years whereas overall the figure has fallen from 670 to 550 per 100 000 employees. The components sector has the worst figures both absolutely and relatively—accounting for half the accidents in the whole industry.

The survey provides a valuable report of the industry which is complementary to 'Company Financial Performance' which was discussed in the November 1974 Journal (p. 592).

† 'Annual Statistical Survey of the Electronics Industry', available from Neddy Books, NEDO, Millbank Tower, Millbank, London SW1P 4QX, price £1.

# Consumer Confusion

Our headline is prompted by the following article published in *The Times* of 2nd January 1975, by whose courtesy it is here reproduced.

## *If Music be the Food of Lovely Machinery, Play on . . .*

**By BERNARD LEVIN**

I bet you don't know what a Piher slider pot is. As a matter of fact, I don't know what it is myself, but at least I know what it is used in connexion with, which is more than you do, I'll be bound. Indeed, I am prepared, for a suitable consideration, to discuss its Ultimate THD, its least usable sensitivity, its square wave performance and its uniform energy response. (It should be obvious that it has side-by-side interlocking facility, and that it is available with taps at $\frac{1}{3}$, $\frac{1}{2}$ and $\frac{2}{3}$ of travel, though whether beer comes out of the taps in question I am in no position to say.)

What is more, I know the answer to the question 'Is it necessary for the head to be moved, in order for the brain to be able to interpret directional information unambiguously?' (Or rather, I do not know the answer, but I know that nobody else does either.)

I do not, of course, have rotatable circular baffles, twin reflex ports or small electrical impedance variation, and I will damned well sue anybody who says I have; on the other hand, I am always in the market for dual layer materials, and if I could only afford it I would use Beryllium for my tweeter dome diaphragms, thus improving (since the stuff has high rigidity but low mass) my transient resolution.

Give up? Then I will reveal all; I have had a new hi-fi system installed, and all that gibberish, incomprehensible though it is to you and me, is the veriest baby-talk to the experts in such arcane mysteries.

My old apparatus had served me faithfully for many years, but an entire new generation of listening-machines had grown up since I got it, and it was clearly getting a bit wheezy, clutching its back and complaining about the weather, and shaking its gnarled fist at passing motor-cars; to put it in less metaphorical terms, the arm tending to jump clean off the record merely because I was playing the Funeral March from *Gotterdämmerung* with the volume set at maximum. I determined, therefore, that I would replace it with something a little more contemporary, and set out to collect an armful of brochures and specialist magazines. A few hours later, I crept home, ashen-faced, and lay down on the sofa, too weak for anything but the Debussy Preludes. For not only had an entirely new language grown up while my attention was distracted; a gigantic industry, its products virtually uncountable, had grown up, too, and I realized that I had not the slightest hope of picking my way through the jungle to safety. So, murmuring 'Keep the river on your right'. I set out in search of an expert.

Before I did that, however, I did some figuring with my trusty pencil. A modern hi-fi system consists, in effect, of some half a dozen items; turntable, cartridge (needle it used to be called when I was young), loudspeakers, tuner and amplifier (one of these, likewise, is what used to be called a radio, though I don't know which one). You can get the tuner and amplifier in one, but then you might want a tape-deck, whatever that might be, and for that matter headphones, so let us say six components altogether for the average fit-up.

Now in some of these categories there are literally hundreds of models available, at all prices and with fancy names; mostly, too, they come with fancy specifications; the Sansui 661 System, for instance, contains, according to the manufacturers and among other things:

The Sansui Sr-212 Automatic Return Turntable with a statically-balanced S-shaped tubular tone arm (with skating-force cancellor), a high performance induced magnetic cartridge and an easy-to-operate out-cut/auto return mechanism.
and
A pair of Sansui's ES-50 2-way 2-speaker wide-sound-dispersion speaker systems of the semi-damped bass-reflex type, with a 35 W maximum power input, a 90 dB/W sensitivity and a 45 to 20,000 Hz frequency range.

And I hope it keeps fine for them, too. But the point is that many of these components are compatible with many of the others, and if we therefore postulate six items, each with (it is a conservative estimate) 80 fully interchangeable models, the number of possible hi-fi systems it would be possible to install is, believe it or not, 262,144,000,000.

Now allowing (an absurdly low figure) half an hour's listening for each, and no time at all for setting them up, to try them all would take, if you spent a third of the day at it, something of the order of 45 million years, and the fact of the matter is that a man as busy as I am simply cannot spare that much time.

So, as I say, I set out in search of an expert, and as it happened I found two. I simply threw myself on the mercy of the first, telling him what I wanted to listen to and what sort of room I wanted to listen to it in. He asked a few questions and, seeing the glazed look in my eyes, asked them again in idiot-proof language, and in no time at all he had come up with a series of answers which I was in no position to dispute even if I had wished to.

The second expert, a colleague of the first, came and installed it; him, I am ashamed to say, I never even met, for he did his mysterious work while I was out, and I got home to find the place full of machines which for some days I did not dare go near, for fear they would seize me in their rotatable circular baffles and do painful things to my impedance. I found the courage to tackle them eventually, and can now operate them with hardly a quaver in my transient resolution or my square wave performance. I have no idea how they work, of course, or indeed which is which, though I *think* I have spotted the turntable because it is round and revolves, which is what even I would expect something called a turntable to do. The sound that comes out of all of it is quite indescribably marvellous (they really *were* experts), and the noise I can make with the Funeral March now is regularly mistaken for the Third World War by my neighbours. I still don't know what a Piher slider pot is, or whether I have got one among my equipment, but I can only say that if I have it is doing its job extraordinarily well, and if I have not, I do not feel the lack of it.

# Conference on 'Advances in Automatic Testing Technology'

Organized by THE INSTITUTION OF ELECTRONIC AND RADIO ENGINEERS with the association of The Institution of Mechanical Engineers, The Institution of Electrical Engineers, The Royal Aeronautical Society, The Institution of Production Engineers, The Institute of Electrical and Electronics Engineers, The Institute of Measurement and Control, The Institute of Quality Assurance, under the aegis of the United Kingdom Automation Council.

## University of Birmingham—15 to 17 April 1975

### Provisional Programme

**Tuesday, 15 April 1974**

TRENDS IN OVERALL SYSTEM DESIGN

'Instrument Design for Automatic Test Equipment'
By J. K. Skilling (*General Radio Co., USA*)

'Automatic Monitoring and Its Effect on System Management'
By D. P. Witty (*Marconi Radar Systems*)

'DELTA—'The Uses of Microprocessors in the Distributed Control of Electronic Testing'
By M. N. Matelan (*MNM Associates, USA*)

'On-line Computer Control for Automatic Testing of I.C. Engines'
By T. F. Jones, (*Rolls Royce (1971)*) and Dr. R. D. Wing (*Imperial College*)

'Automation of Internal Combustion Engine Testing'
By Dr. J. I. Soliman (*Queen Mary College*)

'A Generic Automatic Test System for Turbine Engine Fuel Controls'
By L. R. Hulls (*RCA, USA*)

RATIONALIZATION OF SOFTWARE AND INTERFACES

'A High Level Language for Testing—Selection and Large Scale Use of Protest'
By M. H. Gill (*STL*) and B. S. Jones (*STC*)

'Language Selection for ATE'
By R. J. Patrick (*Marconi-Elliott Avionic Systems*)

'Repair/Discard Decisions—A Mathematical Approach'
By Major P. L. Ost (*REME*)

'Digital Interchange for Instrumentation: A New Interface System'
By D. Dack (*Hewlett-Packard*)

'Data Handling and Communications Techniques for Automatic Fatigue Testing'
By Dr. D. K. Ewing (*National Engineering Laboratory*)

'Fault Dictionary Organization for Modular Systems'
By J. Hlavicka (*Research Institute of Mathematical Machines, Czechoslovakia*)

'A Brief Survey of Standard Interfaces'
By H. A. Dorey (*Solartron*)

'Interface and Protection Circuits for Automatic Test Equipment'
By V. R. Courtice (*STC*)

**Wednesday, 16 April 1974**

APPLICATION TRENDS

'Meeting the Training Needs of Quality Assurance Personnel in Computer Programming for Automatic Test Equipment'
By P. Lorton, Jr. (*University of San Francisco*) and E. J. Reyes (*Defense Contract Administration Services Region, San Francisco*)

'The Quality Assurance Function'
By R. P. Coleman (*Marconi Space and Defence Systems*)

'Using ATE Test Data for Updating Quality Assurance Models'
By J. H. Williams (*UWIST*) and K. A. P. Brown (*EQD, Aquila*)

'Optimum Exponential Smoothing of Quality Control Cusum Charts'
By Mrs. J. M. Brown (*UWIST*)

'The Application of Automatic Testing to the Quality Assurance of Complex Digital Electronic Equipment'
By D. B. Gemmell (*Membrain*)

'Some Facts and Fictions About Testing Logic Circuits'
By A. Boyce and R. G. Coates (*Marconi Research Labs.*)

'Automation of Large Electro-mechanical System Testing'
By Professor D. R. Towill (*UWIST*) and H. V. Harley (*ASWE*)

'Advances in Computer-controlled Realistic Fatigue Testing'
By Dr. F. Sherratt and P. W. Davall (*University of Warwick*)

'Rack Wiring Analyses'
By B. S. Coolbear (*STC*)

'ATE Application—Programs for the Maintenance Engineer'
By Flt.-Lt. N. V. Zotov (*RAF*)

**Thursday, 17 April 1974**

ADVANCES IN ANALYTICAL AND DIAGNOSTIC TECHNIQUES

'Amplitude Domain Automatic Testing'
By Dr. P. A. Payne and J. S. Heard (*UWIST*)

'Automated Dynamic Analysis of Non-linear Control Systems'
By R. V. Webb (*University of Hull*)

'Automatic Frequency Response Testing of Non-linear Control Systems'
By M. C. De'Ath (*Marconi Space and Defence Systems*)

'On-line Tracking of Transfer Function Coefficients via System Simulation'
By R. F. Garzia (*The Babcock & Wilcox Co., USA*)

'An Interactive Approach to Logic Test Generation'
By G. Musgrave, P. L. Flake and M. Shorland (*Brunel University*)

'An Approach to the Diagnosis of Intermittent Faults in Logic Circuits'
By Dr. M. P. Ludlow (*Plessey Telecommunications*)

'Generation Fault Isolation Tests for Logic Networks'
By W. Haydamack (*Hewlett Packard Co., U.S.A.*)

'The Assessment of Circuit Reliability Using Marginal Testing'
By Dr. A. W. Livingstone (*Post Office Research Dept.*)

'Automatic Testing Applied to a Massive Rotating Aerial System'
By Dr. P. A. Payne (*UWIST*) and Dr. R. G. Dawson (*ASWE*)

'Advances in Fault Detection Methods'
By S. Shields (*University of Strathclyde*)

'Implementation of High Speed Programmable Analogue Signal Sources'
By G. M. Ettinger (*Plessey*)

# Members' Appointments

## NEW YEAR HONOURS

The Council has congratulated the following members whose names appear in Her Majesty's New Year Honours List:

KNIGHT BACHELOR

**Dr. Ieuan Maddock, C.B., O.B.E., F.R.S.** (President)

Chief Scientist, Department of Industry.

OFFICERS OF THE CIVIL DIVISION OF THE MOST EXCELLENT ORDER OF THE BRITISH EMPIRE (O.B.E.)

**Victor Alfred Cheeseman, B.Sc.** (Fellow 1958)

Managing Director, Osram (G.E.C.) Ltd.

**Francis Paul Thomson** (Member 1946, Associate 1944)

Associate Consultant, Communications and Equipment Consultants Ltd. (For services to the Giro system.)

## CORPORATE MEMBERS

**Mr. E. Agbana** (Member 1974, Graduate 1971) who has been a Lecturer in Electrical Engineering at Kaduna Polytechnic, Nigeria, since 1971, has been appointed an Electronics Engineer with Mandilas Limited, Lagos.

**Mr. D. A. Cowcher** (Member 1971) has joined British Petroleum Ltd. as a Telecommunications Engineer. He was previously in the Scientific Civil Service, latterly as an Engineer III with the Ministry of Defence (Air) at Headquarters 90 Group RAF.

**Mr. R. G. Dobbin** (Member 1965, Graduate 1957) has been appointed Senior Engineer, Product Assurance, with Stromberg-Carlson at Lake Mary, Florida, USA. For the past four years he has been a Senior Reliability Engineer with the Xerox Corporation at Pittsford, New York.

**Mr. K. P. Edwards** (Member 1963, Graduate 1962) is now with Plessey Telecommunications Ltd., Liverpool, as Quality Engineering Manager.

**Mr. M. J. Elton** (Member 1963, Graduate 1927) who has been with Control Data Sweden AB as Managing Director since 1971, is now General Manager of Control Data Europe Inc. in Brussels.

**Mr. C. Y. Ho** (Member 1970, Graduate 1960) has joined Pye TMC Ltd., St. Mary Cray. He was previously a Senior Development Engineer in the Microwave Division of Standard Telephones and Cables Ltd., Basildon.

**Major G. W. Howard, R. Sigs** (Member 1972, Graduate 1967) has been posted to the School of Signals, Blandford Camp, Dorset as GSO 2 (W) CD/OR.

**Mr. Z. E. Jaworski, Dipl.Ing., D.I.C.** (Member 1966) has been appointed ITU Project Manager at the Advanced Level Telecommunication Training Centre, New Delhi. Mr. Jaworski is on the staff of the City of Birmingham Polytechnic, and in January 1974 he completed a two years' secondment as Adviser in Radio Telemetry to the UNESCO Soil Dynamics Research Team at the National University of Mexico.

**Mr. G. V. Kelly** (Member 1966) has been appointed Manager of Budgetary Planning in the Department of Regional Economic Expansion of the Canadian Government in Ottawa. Before emigrating to Canada in 1966 Mr. Kelly was with Smiths Industries Aviation Division, Cheltenham.

**Mr. W. S. Lucas** (Member 1973, Graduate 1969) has been appointed to head a team of education inspectors appointed by the Ministry of Overseas Development to advise the Government of Hong Kong on curriculum development, teaching methods, workshop layout and equipment in the secondary schools. Mr. Lucas was previously Coordinator of Mathematics and Science subjects at Greenway School, Hillingdon, Middlesex.

**Mr. S. Maher** (Member 1965, Graduate 1955) is now Instructor on the border to border microwave link in the Libyan Arab Republic which is being installed by the Nippon Electric Company.

**Air Commodore J. Matthews** (Member 1971) who was commander of the Regional Signals Support Group HQ AFCENT, Brunssum, in the Netherlands, has now been appointed Director of Weapon and Support Engineering (RAF) at the Ministry of Defence (Air) following his promotion to Air rank.

**Mr. M. J. Moorhouse** (Member 1973, Graduate 1967), recently retired from the RAF, has been appointed Supervisor, Accelerated Coverage Programme, with the Canadian Broadcasting Corporation at Edmonton, Alberta.

**Wing Commander S. K. Morgan, RAF** (Member 1966) has completed a course at the RAF Staff College and has been appointed Commanding Officer EWE & TU, RAF, Wyton, Huntingdonshire.

**Commander B. K. S. Nair, B.Sc.(Eng.), M.E., IN** (Member 1961) who was the Chief Inspector of Warship Equipment, has been appointed Director, Electronic Instrumentation and Controls, Bangalore.

**Major R. W. Stark, B.Sc.(Eng.), R Sigs** (Member 1973, Graduate 1968) is now with 16th Signal Regiment.

**Mr. D. Steadman, B.Sc.(Eng.)** (Member 1968) who joined Cossor Electronics Ltd. in January 1974 as Manufacturing Director, has been appointed Managing Director.

**Mr. T. Vudali** (Member 1973, Graduate 1972) who has been with Calibration Systems Ltd. of Camberley since 1972, latterly as a Senior Standards Engineer, is now studying at Portsmouth Polytechnic for an M.Sc. degree in microwave solid-state physics.

## NON-CORPORATE MEMBERS

**Mr. T. E. Lea** (Graduate 1970) is now Deputy Quality Engineer at 35 Central Workshop REME, Old Dolby, Leicestershire.

**Mr. S. G. Piper** (Graduate 1973), who was a Computer Field Engineer with Rank Xerox Data Systems Ltd., has moved to Hewlett Packard Ltd., Wokingham, to work in a similar capacity.

**Mr. B. H. Quah** (Graduate 1970) has moved from Texas Instruments Malaysia to the General Electric Company Ltd., (Radio and Television) as Quality Engineer at the Assembly Factory in Prai, West Malaysia.

**Mr. I. M. Roger** (Graduate 1966) who was with Dynamco Ltd., has joined NCR (Manufacturing) Ltd., as Senior Electronic Engineer at the Dundee factory.

**Mr. M. R. Shaw** (Graduate 1970) has joined Marconi Space and Defence Systems Ltd., Stanmore, as an Electronics Engineer in the Quality Assurance Department; previously he was an Electronics Engineer with Clifford & Snell Ltd., Sutton.

**Mr. P. J. Shepherd** (Graduate 1972) has been appointed a Project Controller with Marconi Radar Systems Ltd., Chelmsford. For the past two years he has been taking an M.Sc. course in management production at the University of Bradford.

**Mr. A. J. Smart** (Graduate 1970) who was a Microwave Applications and Marketing Engineer with Mullard Ltd., has joined EMI–Varian Ltd. as a Project Sales Engineer, and will be concerned with the marketing of the radar magnetrons previously produced by Mullard but now manufactured by EMI–Varian.

**Lt.-Cdr. R. Stewart, RN** (Graduate 1974) has been posted to HM Dockyard Gibraltar as Assistant Manager, Weapons and Radio. For the past two-and-a-half years he was an Instructor on Computer Systems in HMS *Collingwood*.

**Mr. Ian Whyte, B.Sc.** (Graduate 1954, Associate 1947) has been appointed a Lecturer at Mander College, Bedford. He was previously a Lecturer at Mid-Essex Technical College.

# Obituary

The Council has learned with regret the death of the following member.

**Professor Richard Theile, Dr.Phil.** (Fellow 1954) died on 10th August 1974 at the age of 61 while on holiday in the North Frisian Islands. He leaves a widow.

After obtaining his Abitur at the Realgymnasium Marburg/Lahn, Richard Theile studied at the University of Marburg and the Technische Hochschule in Berlin, receiving his Doctorate in 1938 with a thesis on television pick-up tubes. In 1936 he entered the laboratories of Telefunken in Berlin where he worked until 1945 on research into television pick-up tubes and allied subjects. From 1945–53 he undertook alternately teaching and research activities, lecturing at the University of Marburg and leading a research group working on the development of the super-iconoscope at the laboratories of Pye Limited in Cambridge.

In 1953 Professor Theile was appointed Head of the Television Department of the Rundfunk-Technisches Institut in Nuremberg. Shortly after the foundation of the Institut für Runkfunktechnik in 1956, he took charge of the Munich Centre and from 1960 he held the post of Director and Administrator of both the Munich and Hamburg Centres until his death.

In 1952 he was co-author of two papers presented in the Journal, for one of which, 'The application of negative feedback to flying-spot scanners', he shared the Louis Sterling Premium. His services to radio and television technology have won him recognition both in his own country and abroad, and he has been posthumously awarded a Special Commendation by the Society of Motion Picture and Television Engineers.

# *Letter to the Editor*

**From: N. C. Davies,** B.Sc., C.Eng., M.I.E.R.E.

## A.C.U.C.E. Memorial to Professor Emrys Williams

Former students and colleagues of the late Professor Emrys Williams will have heard with sadness of his untimely death last year and may wish to know that a Memorial Fund has been established.

He was already a distinguished engineer when in 1954 he was appointed to the newly established Chair of Electrical Engineering at University College, Cardiff. From Cardiff, he travelled all over the world to represent our own Institution of which he was a Past President, and as Visiting Professor and External Examiner to Universities.

His active interest in many fields was mentioned in the Director's very sincere tribute last year. Many times he gave help discreetly; at times people did not know he had stepped in to help them. Also he delighted in helping those who helped others.

At the time of his death he was President of the Association of Cardiff University College Engineers, having been an active member for many years. The Association, whose members are mainly past students, together with past and present members of staff of the Engineering Departments, is making a Collection for the Memorial Fund as its own mark of respect.

We invite any of his past students and colleagues who would like to contribute to the Memorial Fund to send a cheque payable to 'ACUCE Collection for the Emrys Williams Memorial Fund' to

The Secretary, ACUCE, University College,
Newport Road, Cardiff CF2 1TA.

It is hoped that an announcement about the Memorial Fund will be made at our Cardiff Reunion on Friday, 7th March 1975. I will be glad to give further information to anyone who writes to me at the College (with S.A.E. please) or telephones me at home in London 01-455 5910.

NORMAN C. DAVIES

Association of Cardiff University
College Engineers,
The Engineering Departments,
University College, Newport Road,
Cardiff CF2 1TA

*14th January 1975*

# IMEKO VII

The 7th Congress of the International Measurement Confederation will be held in London from 10th-14th May 1976, and is being organized by the Institute of Measurement and Control which is the UK member society of IMEKO; the IERE is one of the co-sponsoring organizations which also include the Institutions of Chemical, Electrical and Mechanical Engineers, the Institute of Physics, the Chemical Society and the Institute of Petroleum.

IMEKO Congresses customarily have a theme and for the 7th Congress it will be 'Practical Measurements for Improving Efficiency.' Offers of papers are now invited to fit this theme and assist cross fertilization of ideas and technology transfer between the many different specialist interests in IMEKO's field. As well as contributions related to application areas and techniques papers are also being invited for a session examining the difficulties caused by the different instrument requirements on either side of the Atlantic, differences caused partly by variations in legal requirements and partly by the use of metric and non-metric systems.

Offers of papers and requests for further information should be sent to The Secretary, Institute of Measurement and Control, 20 Peel Street, London W.8, in the case of UK contributions, or to the member organization in other countries, or otherwise to the IMEKO Secretariat, 1371 Budapest 5, POB 457, Hungary.

# INSTITUTION OF ELECTRONIC AND RADIO ENGINEERS

## Applicants for Election and Transfer

THE MEMBERSHIP COMMITTEE at its meetings on 28th December 1973 and 12th December 1974 recommended to the Council the election and transfer of 23 candidates to Corporate Membership of the Institution and the election and transfer of 15 candidates to Graduateship and Associateship. In accordance with Bye-law 23, the Council has directed that the names of the following candidates shall be published under the grade of membership to which election or transfer is proposed by the Council. Any communication from Corporate Members concerning those proposed elections must be addressed by letter to the Secretary within twenty-eight days after the publication of these details.

### *Meeting: 28th December 1973 (Membership Approval List No. 203)*

#### GREAT BRITAIN AND IRELAND

**CORPORATE MEMBERS**

**Transfer from Graduate to Member**

BOWN, Peter Edwards. *St. Johns Wood, London.*
CHRISTIE, Philip William. *Wimborne, Dorset.*
JOHNSON, James Geoffrey. *Oakley, Dorset.*
MARTIN, Denis Norman. *Luton, Bedfordshire.*

#### OVERSEAS

**CORPORATE MEMBERS**

**Transfer from Graduate to Member**

CARMEL, Ilan. *Kiryat Motzkin, Israel.*

### *Meeting: 12th December 1974 (Membership Approval List No. 204)*

#### GREAT BRITAIN AND IRELAND

**CORPORATE MEMBERS**

**Transfer from Member to Fellow**

THOMAS, Victor Francis. *Norwich, Norfolk.*
WILSON, Frederick Arthur. *London.*

**Transfer from Graduate to Member**

DONNELLY, Paul. *Stockport, Cheshire.*
FAULKNER, Harry. *Warrington, Cheshire.*
GAVIN, Philip. *Dunfermline, Fife.*
HALL, James Anthony. *Malvern, Worcestershire.*
HAYWARD, Nicholas Samuel John. *Malvern Wells, Worcestershire.*
POULTER, Stuart Edmond. *Maidstone, Kent.*
ROE, John Reginald. *Witham, Essex.*

**Transfer from Student to Member**

BLOOR, John Eric. *Cheadle Hulme, Cheshire.*

**Direct Election to Member**

CLARK, Richard Jonathan. *Basingstoke, Hampshire.*
CLARK, Ronald Davidson. *Clarkston, Glasgow.*
GORDON, Meredith. *Purbrook, Hampshire.*
MAY, Colin Percy. *Great Cornard, Suffolk.*
PRIESTLEY, Barry. *Slough, Buckinghamshire.*
SCORER, Alexander Peter Paul. *London.*
SUGUNENDRAN, Selvaratnam Arulchelvan. *Surbiton, Surrey.*

**NON-CORPORATE MEMBERS**

**Transfer from Student to Graduate**

MILES, Howard. *Melton Mowbray, Leicestershire.*

**Direct Election to Graduate**

BANSI, Palwinder Singh. *Basildon, Essex.*

**Transfer from Graduate to Associate Member**

HICKLING, Alfred. *Malvern, Worcestershire.*

**Direct Election to Associate Member**

EATON, Roy Clement. *Moreton in Marsh, Gloucestershire.*
GILL, Anthony Cuthbert. *Plaistow, London.*
HARPER, David William. *Rainham, Kent.*
SHOESMITH, Brian Arthur. *High Wycombe, Buckinghamshire.*
SNOOK, Stephen Arthur. *London.*
WELSTEAD, Peter James. *Gravesham, Kent.*

**STUDENTS REGISTERED**

GRUBB, John Arthur. *Dublin.*
GRIFFIN, Douglas Jay. *Wigtownshire, Scotland.*
PUDNER, Anthony Richard Gordon. *Portswood, Southampton.*

#### OVERSEAS

**CORPORATE MEMBERS**

**Transfer from Member to Fellow**

EL-JADIRY, Fakhry Karim. *Basrah, Republic of Iraq.*

**Transfer from Graduate to Member**

LUI, Wing Yiu Jimmy. *Happy Valley, Hong Kong.*

**Direct Election to Member**

BHAT, S. J. *Manipal, India.*
CALVERT, Geoffrey William. *Quebec, Canada.*

**NON-CORPORATE MEMBERS**

**Direct Election to Graduate**

LAM, Kay Leung George. *Kowloon, Hong Kong.*

**Direct Election to Associate Member**

NWACHUKWU, Christoper Azuka. *Lagos, Nigeria.*
MOK, Yuk Bio. *Sarawak, Malaysia.*
COLAM, Royston Frederick. *Salisbury, Rhodesia.*

**Transfer from Student to Associate**

DAMASUS, Augustine Uche. *Lagos, Nigeria.*

**Direct Election to Associate**

KERRIGAN, Brian. *Edmonton, Canada.*

**STUDENTS REGISTERED**

MANAMPERI, Asela Bandara. *Ampitiya, Sri Lanka.*

*Correction.* **Membership List No. 192, published September 1974**

**Transfer from Graduate to Member**

EMERSON, Roger Whyndham, *should read:*
EMBERSON, Roger Whyndham. *High Ongar, Essex.*

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## Certified Diploma in Accounting and Finance

The results of the June examination for the Certified Diploma in Accounting and Finance have been announced by the Association of Certified Accountants. Out of 309 candidates sitting for the examination, 190 were successful and about a half of those who passed were associated with chartered engineering institutions. The following members of the IERE have gained the Diploma:

**Mr. R. E. Bona** (Member 1968, Graduate 1966) who is Deputy Manager of the Management Services Department at the M.O.D. Agency Factory of EMI Ltd., at Hayes.

**Mr. M. J. Clements** (Member 1969, Graduate 1966) Group Engineering Manager with Electrocomponents Ltd.

**Mr. P. C. D. Dann, B.Sc.(Eng.)** (Fellow 1973, Member 1962) who joined Elco Plastics Limited in June as General Manager (Managing Director designate); for the previous nine years he was with the Plessey Company, and latterly was concerned with the production of u.h.f. television transposers.

**Mr. B. L. Fowler** (Member 1967, Graduate 1965) Quality Control Manager with Stone Manganese Marine Ltd.

**Mr. A. E. Fyfe** (Member 1971, Graduate 1969) Manager (Engineering) of the West Coast of America Telegraph Company in Lima, Peru.

**Mr. A. J. Straker** (Member 1969, Graduate 1967) Product Manager with Marconi Space and Defence Systems, Frinley.

## 1974 MacRobert Award for the Manufacture of High Activity Catalysts

The 1974 MacRobert Award, the major engineering award in Great Britain, has been won by a team of five nominated by ICI Agricultural Division for their contribution to the development and manufacture of high activity catalysts. They are Dr. T. J. P. Pearse, Mr. G. W. Bridger, Mr. P. Davies, Dr. J. T. Gallagher and Dr. D. Cornthwaite. The Award, made annually by the Council of Engineering Institutions on behalf of the MacRobert Trusts, consists of a Gold Medal and £25,000 prize money. It is presented in recognition of an outstanding contribution by way of innovation in engineering or the physical technologies or in the application of the physical sciences which has enhanced or will enhance the prestige and prosperity of the United Kingdom.

In the 1960s a significant advance in the technology of catalyst manufacture was made in the ICI Billingham laboratories. A systematic examination of the manufacturing costs of the established 350-atmospheres process for the synthesis of methanol showed that important economies could be achieved if it was possible to operate the process at lower pressures. This could not be done unless a better catalyst could be developed and the ICI laboratories set out to produce a catalyst having the required characteristics.

The ICI research successfully established novel procedures for the manufacture of improved catalysts having high activity which is retained in service. The new procedures involve continuous precipitation instead of the batch methods previously employed, and the components of the catalyst, copper, zinc and alumina, are precipitated simultaneously under precisely controlled conditions. As a result of this invention ICI was able in 1966 to introduce its new low temperature, low pressure process for the synthesis of methanol in which the new catalyst has the very satisfactory life of two to three years.

Methanol plants using the new catalysts have lower capital and operating costs than the classical 350 atmospheres plants and manufacturers all over the world have adopted the process. ICI has built two plants, and twenty-three of the twenty-nine new methanol plants constructed or being designed in the world since 1966 use the process. Together they will account for over one-third of the world's total production of methanol and their construction has brought £18M to the UK in licence fees, catalyst sales, etc.

The new precipitation method is being applied to other catalysts, notably an improved catalyst for the low temperature shift process employed in the production of gas for ammonia synthesis. Because of its better performance compared with other available catalysts, this catalyst already accounts for 75% of the world market and 90% of the US market; sales so far have brought £3M to the UK, and £7M to ICI'S associate company in the USA, Katalco Corporation.

In his citation for the Award, Lord Hinton of Bankside, Chairman of the Evaluation Committee, said that 'the Committee feel that the brilliant and painstaking work done by ICI has made an outstanding contribution to British prestige and prosperity'.

## V.H.F.–F.M. Broadcasting and Dolby 'B'

The application of the Dolby 'B' noise reduction system to v.h.f.–f.m. broadcasting is a suggested development which is currently causing some controversy. The BBC is of course an interested party and has recently issued a note explaining its attitude. It is pointed out that the BBC is always looking at ways of improving its services but is not convinced that the addition of Dolby 'B' would be wise.

As applied to tape-recording, Dolby 'B' involves the boosting, in a special way, of low-level signals prior to recording. This compression of the dynamic range is complemented by expansion in the replay chain in order to restore the balance at all levels. There seems to be no technical reason why such a 'companding' process should not be successful with f.m. broadcasting and it would certainly bring about an improvement in signal/noise ratio for some listeners at the fringe of the transmitter service area. The broadcaster, however, must consider whether such improvement, for relatively few listeners, would justify the requirement that all existing v.h.f. receivers would have to be replaced or modified. This is because the introduction of compression at the sending end, without complementary expansion in the receiver would, inevitably, involve a degradation in overall fidelity. This serious question of compatibility seems to have been underrated by those who advocate the application of Dolby 'B' to broadcasting.

It has been claimed that, with receivers having a 75-μs de-emphasis time-constant (as in America), the use of Dolby 'B' together with a 25-μs pre-emphasis in the transmissions gives adequate compatibility. It is also true that the claim is questioned in some circles. There is doubt whether a combination of compandor and time-constant could be found which would match up to the standard of quality given by a good European receiver/tuner with a 50-μs constant and the established broadcasting standard.

As a result of a great deal of work, the BBC has recently installed 'variable de-emphasis' limiters for services which carry most of the stereophonic transmissions. The principle is that for the majority of the time the broadcast is with the conventional 50-μs pre-emphasis, with assurance that all receivers are fitted with the complementary 50-μs de-emphasis, but when in exceptional circumstances there is a very large amplitude, high frequency content, a momentary reduction of pre-emphasis (not clipping) is automatically introduced. Over-deviation, arising from the use of pre-emphasis in the system, can be avoided without having to reduce the gain at low audio frequencies. Very careful testing has shown that the action of this special limiter is barely detectable subjectively by the most expert observer, even when he has access to the original material.

To ensure that the ordinary listener with a standard receiver has the maximum signal level possible, consistent with the minimum distortion, a smaller margin of protection against over-deviation is allowed for stereo broadcasts compared to mono. This has the effect of improving the signal-to-noise ratio by about 2–3 dB. A further improvement of about 3–4 dB can be achieved with the use of the variable de-emphasis limiter.

# Forthcoming Institution Meetings

## London Meetings

*Wednesday, 26th February*

COMMUNICATIONS GROUP

**Low Attenuation Corrugated Waveguides**

By Professor P. J. B. Clarricoats and Dr. D. Olver (*Queen Mary College*)

IERE Lecture Room, 6 p.m. (Tea 5.30 p.m.)

*Wednesday, 5th March*

COMPONENTS AND CIRCUITS GROUP

**Colloquium on EXPLOITING THE PROM**

IERE Lecture Room, 2 p.m. Further details to be announced.

*Thursday, 6th March*

EDUCATION AND TRAINING GROUP

**Colloquium on MODULAR COURSES**

IERE Lecture Room, 10 a.m. Further details to be announced.

*Wednesday, 12th March*

AEROSPACE, MARITIME AND MILITARY SYSTEMS GROUP

**Acoustic Holography**

By Professor J. W. R. Griffiths (*University of Technology, Loughborough*)

IERE Lecture Room, 6 p.m. (Tea 5.30 p.m.)

*Wednesday, 19th March*

AUTOMATION AND CONTROL SYSTEMS GROUP

**Colloquium on ON-LINE CALCULATORS AND INSTRUMENTATION**

IERE Lecture Room, 10 a.m. Further details to be announced.

*Wednesday, 9th April*

AEROSPACE, MARITIME AND MILITARY SYSTEMS GROUP

**Colloquium on RADAR AND ASSOCIATED SYSTEMS FOR VEHICLE GUIDANCE**

IERE Lecture Room, 2 p.m. Further details to be announced.

*Thursday, 10th April*

JOINT IERE/IEE COMPUTER GROUP

**Colloquium on COMPUTERS IN TRANSPORT**

IERE Lecture Room, 10 a.m. Details to be announced.

*Wednesday, 23rd April*

COMPONENTS AND CIRCUITS GROUP

**Colloquium on RECENT DEVELOPMENTS IN TURNTABLE DESIGN**

IERE Lecture Room, 10 a.m. Further details to be announced.

*Wednesday, 30th April*

INAUGURAL MEETING OF THE MEASUREMENTS AND INSTRUMENTS GROUP

**Colloquium on MEASURING INSTRUMENTS FOR THE TESTING OF MATERIALS AND COMPONENTS**

IERE Lecture Room, 2 p.m. Further details to be announced.

*Wednesday, 7th May*

COMMUNICATIONS GROUP

**Colloquium on MILLIMETRIC WAVE PROPAGATION**

IERE Lecture Room, 2 p.m. Further details to be announced.

*Wednesday, 14th May*

MANAGEMENT TECHNIQUES GROUP

**Colloquium on THE JAPANESE ELECTRONICS INDUSTRY**

IERE Lecture Room. Further details to be announced.

*Wednesday, 21st May*

EDUCATION AND TRAINING GROUP

**Colloquium on THE CEI EXAMINATION AND THE COLLEGES**

IERE Lecture Room, 2.30 p.m. Further details to be announced.

*Thursday, 22nd May*

JOINT IERE/IEE COMPUTER GROUP

**Colloquium on DISTRIBUTED INFORMATION SYSTEMS**

IERE Lecture Room, 2.30 p.m. Further details to be announced.

## Southern Section

*Wednesday, 26th February*

**Time Series Feature Detection**

By Dr. D. W. Thomas (*University of Southampton*)

Lanchester Theatre, Southampton University, 6.30 p.m.

*Tuesday, 4th March*

**Electronics in Yachts**

By P. I. Pelham (*Brookes & Gatehouse*)

Bournemouth College of Technology, 7 p.m.

*Wednesday, 5th March*

**Project Management in the 1970s**

By R. H. Bradnam (*Urwick Technology Management*)

Brighton Technical College, 7 p.m.

*Wednesday, 12th March*

ANNUAL GENERAL MEETING OF THE SECTION, 7 p.m.

followed by

**LOUDSPEAKER ENCLOSURES**

By A. Dyke (*Plessey, Roke Manor*)

Room AB 011, Portsmouth Polytechnic, Park Road.

*Thursday, 20th March*

**Time Series Feature Detection**

By Dr. D. W. Thomas (*University of Southampton*)

South Dorset Technical College, 6.30 p.m.

*Wednesday, 26th March*

JOINT MEETING WITH IEE

**Halfday Symposium on Television Topics**

(Including a tour of I.B.A. Laboratories)

IBA, Crawley Court, Winchester, 2.30 p.m.

## Thames Valley Section

*Thursday, 6th March*

**Liquid Crystals and Device Applications**

By I. A. Shanks (*RRE Malvern*)

J. J. Thomson Physical Laboratory, University of Reading, Whiteknights Park, Reading, 7.30 p.m.

*Tuesday, 8th April*

**PROJECT MANAGEMENT**

By Dr. I. Maddock (*Department of Industry*)

J. J. Thomson Physical Laboratory, University of Reading, Whiteknights Park, Reading, 7.45 p.m.

## Kent Section

*Thursday, 6th March*

**Flight Recording in Civil Aviation**

By P. Waller (*British Airways European Division, Heathrow*)

Lecture Theatre 18, Medway and Maidstone College of Technology, Maidstone Road, Chatham, 7 p.m.

*Thursday, 3rd April*

ANNUAL GENERAL MEETING at 7 p.m.

followed by

PRESENTATION OF CERTIFICATES OF CORPORATE MEMBERSHIP

By Harvey F. Schwarz (Past President)

followed by

**NAVIGATION HAZARD WARNING SYSTEMS USING RADAR AND COMPUTER**

By Bruce Williams (IBM (UK) )

The Tollgate Motel, Watling Street, Gravesend, Kent.

## East Anglian Section

*Thursday, 20th February*

JOINT MEETING WITH IEE

**Integrated Circuits for Analogue Functions**

By Dr. J. Highway (*Plessey*)

University Engineering Laboratories, Trumpington Street, Cambridge, 6.30 p.m. (Tea 6 p.m.)

## South Midland Section

*Thursday, 13th March*

G. C. Club, G.C.H.Q. Benhall, Cheltenham. 7.30 p.m. Details to be announced.

*Thursday, 17th April*

**Engineering Innovation in Mini-computer Design**

By A. Colvin (*CAI*)

B.B.C. Club, Evesham, 7.30 p.m.

To be followed by Annual General Meeting.

*Friday, 23rd May*

A Social Function at Evesham to be arranged.

## West Midland Section

*Thursday, 20th February*

JOINT MEETING WITH IEE AND IPOEE

**Communications—Bit by Bit**

By H. B. Law (*PO Research Department*)

PO Training Centre, Duncan Hall, Stone, Staffs, 7.15 p.m.

*Thursday, 6th March*

JOINT MEETING WITH IEE

**Developments in Train Control and Automation**

By B. Mellitt (*University of Birmingham*)

Lanchester Polytechnic, Coventry, 7.15 p.m.

*Tuesday, 22nd April*

ANNUAL GENERAL MEETING

Followed by

**Quadraphonics**

By Dr. K. Barker (*University of Sheffield*)

The Polytechnic, Wolverhampton, 7 p.m.

## East Midland Section

*Tuesday, 4th March*

JOINT MEETING WITH IEE

**The Implementation of Arithmetic Processes in LSI Microelectronics**

By P. Van Cuylenburg (*Texas Instruments*)

Edward Herbert Building, Loughborough University, 7 p.m. (Tea 6.30 p.m.)

## South Western Section

*Wednesday, 19th February*

JOINT MEETING WITH RAeS AND IEE

**Engine Testing using Advanced Techniques**

By P. A. E. Stewart (*Rolls Royce*)

No. 4 Lecture Theatre, School of Chemistry, University of Bristol, 7 p.m. (Tea 6.30 p.m.)

*Tuesday, 11th March*

JOINT MEETING WITH IEE

**Ambisonics**

By Professor P. B. Fellgett (*Reading University*)

Main Lecture Theatre, University of Bath, 6 p.m. (Tea 5.30 p.m.)

*Monday, 7th April*

JOINT MEETING WITH IEE

**Telemetry**

By C. J. Williams (*Quindar-Wirral Automation*)

Queen's Building, Bristol, 6 p.m. (Tea 5.30 p.m.)

*Wednesday, 23rd April*

**Oceanography**

By M. J. Tucker (*Institute of Oceanographic Sciences*)

No. 4 Lecture Theatre, School of Chemistry, University of Bristol, 7 p.m. (Tea 6.30 p.m.)

*Monday, 5th May*

ANNUAL GENERAL MEETING

The Royal Hotel, Bristol, 7 p.m. (Tea 6.30 p.m.)

## Yorkshire Section

*Thursday, 20th February*

JOINT MEETING WITH IEE

**Oracle—Information by Domestic TV**

By G. A. McKenzie and P. R. Hutt (*IBA*)

Yorkshire Television Studios, Leeds, 6.30 p.m.

*Wednesday, 19th March*

**Digital Techniques Applied to Television**

By Dr. O. Downing

Bradford University, 6.30 p.m.

*Friday, 25th April*

ANNUAL GENERAL MEETING

Leeds University, 7 p.m. (Tea 6.30 p.m.)

## Merseyside Section

*Wednesday, 12th March*

**The Application of Computers to the Wide Area Control of Road Traffic**

By D. W. Honey (*Liverpool Corporation*)

Department of Electrical Engineering and Electronics, University of Liverpool, 7 p.m. (Tea 6.30 p.m.)

## North Eastern Section

*March*

JOINT MEETING WITH BRITISH ACOUSTICAL SOCIETY

Details to be announced.

*Wednesday, 9th April*

**Military Communications by Satellite**

By W. M. Lovell (*Marconi Space and Defence Systems*)

## South Wales Section

*Wednesday, 12th March*

**Impulse Measurement Techniques**

By J. Kuehn (*Bruel and Kjaer*)

Department of Applied Physics and Electronics, UWIST, Cardiff, 6.30 p.m. (Tea 5.30 p.m.)

*Thursday, 10th April*

JOINT MEETING WITH IEE

**Tomorrow's World in Microwave Communications**

By T. R. Rowbotham (*Post Office Research*)

University College, Swansea, 6.15 p.m. (Tea 5.30 p.m.)

*Wednesday, 22nd January*

JOINT MEETINGS WITH IEE

**Optoelectronics**

Dr. W. Oliver (*Robert Gordon's Institute of Technology*)

*Wednesday, 5th March*

Napier College of Science and Technology, Colinton Road, Edinburgh EH10 5DT, 7 p.m.

*Thursday, 6th March*

Glasgow College of Technology, Hanover Street, Glasgow, 7 p.m.

MINISTRY OF DEFENCE

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**SCHOOL OF SIGNALS, BLANDFORD, DORSET**

# Lecturers Grade 1 (2 posts)

Those appointed will join a civilian lecturing staff of eight under a Principal Lecturer who form a department teaching telecommunication engineering and associated electronics to graduate officers, and to senior non-commissioned officers taking Higher National Certificate. The School has teaching laboratories and a Hewlett Packard 3000 computer system which give facilities comparable to those in Polytechnic. The School is housed in modern buildings one mile from Blandford in attractive surroundings. Social and sporting facilities are excellent.

**Qualifications and Experience.** For both posts a relevant degree is essential. For the first, a knowledge of digital computers and experience in using digital integrated circuits is required; for the second, candidates should have some experience in digital communication systems and/or radio wave propagation and antennas.

**Salary and conditions.** These are in accordance with the Scales of Salaries for Teachers in Establishments for Further Education, i.e. £1800–£3045 p.a. plus Cost of Living Allowance. A slightly longer working year carries an allowance of £397 p.a.

**Applications.** Application forms and further particulars may be obtained from Ministry of Defence, CM(S)4(L) Room 342, Lacon House, Theobalds Road, London, WC1X 8RY, and should reach this address not later than 10 days from the date of this publication, quoting reference AW/1351.

# M.Sc. Course in Electrical Engineering

with specialisation in any one of the following:

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**Communication Systems,**
**Electronic Instrumentation Systems,**
**Control Engineering and Digital Electronic Systems,**
**Design of Pulse and Digital Circuits and Systems,**

The Course, which commences in October 1975, may be taken on a Full Time, Part Time, sandwich or Block Release basis, and is open to applicants who will have graduated in Engineering or Science, or who will hold equivalent qualifications, by that date. The Science Research Council has accepted the Course as suitable for the tenure of its Advanced Course Studentships.

**A Diploma Course, in some of the above topics or in Power Systems, is also open to applicants with the above, or slightly lower qualifications.**

## Research in Electrical Engineering

Applications are also invited from similarly qualified persons who wish to pursue a course of research leading to the Degree of M.Phil. or Ph.D. in any of the above subjects.

Application forms and further particulars from the Head of the Department of Electrical Engineering (Ref: M.Sc. 4), The University of Aston in Birmingham, BIRMINGHAM B4 7PB.

THE UNIVERSITY OF ASTON IN BIRMINGHAM

**UNIVERSITY OF SURREY**

Department of
Electronic and Electrical Engineering

# Plessey Research Fellowship

## Salary up to £3000 p.a.

To commemorate the late Alan J. Oxford, head of the Research Department, Plessey Company, Westleigh, Havant, the Plessey Company has established a Fellowship with the Department of Electronic and Electrical Engineering at the University of Surrey.

Applications are invited from people interested in investigating aspects of ELECTRONIC INFORMATION SYSTEMS, such as the organization and design of complex data processing systems, the balance between analogue and digital processing methods, the influence of the system and human attributes on the design of display equipments and sensors, operation with multi-spectral sensors, the application of feedback loops and adaptive techniques, and operator interaction and decision-making.

Applicants should hold a high quality first degree, or have adequate experience in industrial employment at an appropriate level. They will be expected to put forward specific research proposals within the area outlined above. The appointment will be for two or three years, and applicants will be eligible to register for a higher degree.

Further particulars may be obtained from the Academic Registrar (LFG), University of Surrey, Guildford, Surrey GU2 5XH, or Tel: Guildford 71281, Ext. 452, and to whom applications, in the form of a curriculum vitae, including the names and addresses of two referees should be sent.

UWIST CARDIFF
University of Wales Institute of Science and Technology

**Department of Applied Physics and Electronics**

## M.Sc./DIPLOMA COURSE IN ELECTRONICS

Applications are invited for places in the full-time one-year M.Sc./Diploma course in Electronics, commencing 1st October, 1975.

**Further details may be obtained from the Academic Registrar, UWIST, Cardiff CF1 3NU.**

Application forms should be completed and returned to the College as soon as possible.

The Proprietors of British Patent No. 1043741 for "Method and apparatus for producing small electrical components" desire to enter into negotiations for the sale of the patent, or for the grant of licences thereunder. Further particulars may be obtained from Marks & Clerk, 57/60 Lincoln's Inn Fields, London WC2A 3LS.

# INSTITUTION RECORDS

## MEMBERS' CHANGE OF ADDRESS AND/OR APPOINTMENT

It would greatly assist in keeping the Institution's membership records up-to-date if members would inform Headquarters immediately on changing their address and/or appointment. The form below will be published from time to time—no accompanying letter is required. It would be appreciated if members would use BLOCK LETTERS in completing the form.

..........................................................................................................................................

**To: The Secretary,**
**The Institution of Electronic and Radio Engineers,**
**8–9 Bedford Square, London WC1B 3RG.**

**Date** ..............................

**CHANGE OF ADDRESS AND/OR APPOINTMENT**

As from .............................. my address is ..........................................................................

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As from .............................. my appointment is:

Description ..........................................................................

Name of Organization ..........................................................................

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Date . . . . . . . . . . . . . . . Signed . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .

# International Conference on 'Advances in Automatic Testing Technology'

BIRMINGHAM—15th to 17th APRIL, 1975

Joint Conference Secretariat, IERE,
8-9 Bedford Square, London WC1B 3RG.

Please send me.................registration form(s) and further information about the Conference as soon as it is available.

Name:...................................................................................................

Address:...............................................................................................

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# Conferences, Courses and Exhibitions, 1975-76

The date and page references in italics at the head of an item are to issues of *The Radio and Electronic Engineer* in which fuller notices have been published. An asterisk (*) indicates a new item or information which has been amended since the previous issue. The symbol (●) indicates that the IERE has organized the event or is a participating body.

*Further information should be obtained from the addresses given*

**1975**

March 3–11 LONDON
**50th Convention of the Audio Engineering Society**
Mr. E. J. Franklin, A.E.S. Convention, Eccleston Road, Maidstone, Kent ME15 6AU

* March 4–6 NUREMBERG
**Conference on Satellite Radio Systems** (VDE/NTG)
VDE-Sekretariat, D-600, Frankfurt/Main 70, Stresemannallee 21.

● March 4–7 LONDON *March 1974, p. 176*
**Conference on Low Light and Thermal Imaging Systems** (IEE, IERE, IoP, IEEE)
Conference Department, IEE, Savoy Place, London WC2R 0BL

● March 11–12 LONDON
**Symposium on The Use of Computers in Shipboard Automation** (RINA, IMarE, IEE, IERE, RIN, Nautical Institute)
The Secretary, Royal Institution of Naval Architects, 10 Upper Belgrave Street, London SW1X 8BQ

March 11–23 ROME
**22nd International Exhibition of Advanced Technology and Congress on Electronics**
Rassegna Internazionale Elettronica, Via Crescenzio 9, 00193 Rome

* March 13–14 STUTTGART
**Conference on Computer Aided Circuit Design** (VDI/NTG/DGQ)
VDE-Sekretariat, D-6000, Frankfurt/Main 70, Stresemannallee 21.

March 16–21 BRIGHTON, ENGLAND
**Oceanology International 75 Conference and Exhibition**
BPS Exhibitions Limited, 4 Seaford Court, 220–222 Great Portland Street, London W1N 5HH

March 19 LONDON
**Seminar on Plastics in Light Engineering**
(Plastics Institute, Sira Institute)
Mr. G. Dunn, Sira Institute Ltd., South Hill, Chislehurst, Kent BR7 5EH

March 24–26 LONDON
**Ultrasonics Industrial 1975—Conference and Exhibition**
IPC Science and Technology Press Ltd., 32 High Street, Guildford, Surrey GU1 3EW

March 24–26 OXFORD
**Symposium on Computer Assisted Learning in Science and Engineering**
Mr. E. J. H. Birch, Department of Science, Oxford Polytechnic, Headington Road, Oxford

March 24–27 CRANFIELD *March 1974, p. 176*
**8th International Aerospace Instrumentation Symposium** (Cranfield Institute of Technology, RAeS, IMC, ISA)
Mr. N. O. Matthews, Department of Flight, Cranfield Institute of Technology, Cranfield, Bedford, England

March 25–April 4 SHANGHAI *May 1974, p. 287*
**British Machine Tools and Scientific Instruments Exhibition** (MTTA, SIMA-GTMA)
British Overseas Trade Board, Fairs and Promotions Branch, 1 Victoria Street, London SW1H 0ES

April 2–8 PARIS
**18th International Electronic Components Exhibition**
FNIE, 16 Rue de Presles, 75740 Paris, Cedex 15

April 2–4 PARIS
**International Conference on Substitution Materials for Electronic Components** (FNIE)
FNIE, 16 Rue de Presles, 75740 Paris, Cedex 15.

* April 2–8 PARIS
**4th International Audiovisual and Communication Exhibition**
SDSA, 14 Rue de Presles, 75740 Paris. Cedex 15

* ● April 3–4 LONDON *January 1975, p. 83*
**Conference on Detail Design** (IMechE, CEI)
Conference Department, IMechE, 1 Birdcage Walk, London SW1H 9JJ

April 8–9 LEICESTER
**2nd Inspection and Quality Control Conference** (IProdE and IQA)
Miss Rosemary Willson, Conference Communication, Hollytree House, 1 Gorse Lane, Wrecclesham, Farnham, Surrey GU10 4SD

● April 8–10 LONDON
**Conference on Satellite Communication Systems Technology** (IEE, IERE)
Conference Department, IEE, Savoy Place, London WC1B 3RG

April 8–11 LOUGHBOROUGH
**Symposium on Incoherent Light Sources** (IoP, IEE, University of Loughborough)
Institute of Physics, 47 Belgrave Square, London SW1X 8QX

April 8–11 NEW YORK
**IEEE International Convention and Exhibition**
IEEE Intercon, 3600 Wilshire Boulevard, Los Angeles, Calif. 90010

April 9 HATFIELD
**Symposium on Noise in Systems**
The Institute of Mathematics and its Applications, Maitland House, Warrior Square, Southend-on-Sea, Essex SS1 2JY

April 14–17 LONDON
**13th International Conference on Magnetics (Intermag)** (IoP, IEEE, IEE)
Institute of Physics, 47 Belgrave Square, London SW1X 8QX

April 14–18 LONDON
**LABEX International 75**
UTP Exhibitions Ltd., 121 King Street, London W5 9JG

● April 15–17 BIRMINGHAM *January 1975, p. 86*
**Conference on Advances in Automatic Testing Technology** (IERE, IEE, IMechE, IProdE, RAeS, IMC, IEEE)
IERE, 8–9 Bedford Square, London WC1B 3RG

April 15–17 OXFORD
**Conference on Scientific Aids in Hospital Diagnosis**
Mr. R. E. George, SAMB Publicity Officer, Department of Clinical Physics and Bioengineering, Guy's Hospital, London SE1 9RT

April 23–27 HEATHROW, MIDDLESEX
**SONEX 75—European High Fidelity Exhibition**
British Audio Promotions Ltd., 414a Edgware Road, London W2 1ED

● April 22–24 SHEFFIELD *January 1974, p. 51*
**Trends in On-Line Computer Control Systems** (IEE, IERE, IMA, IoP, IMC, IChemE)
Conference Department, IEE, Savoy Place, London WC2R 0BL

* ● April 29–30 LONDON
**Conference on Terotechnology for Better Resource Management** (Inter-Institution Terotechnology Group, D of I Committee for Terotechnology, *The Engineer*)
Miss Rosemary Willson, Conference Communication, Hollytree House, 1 Gorse Lane, Wrecclesham, Farnham, Surrey GU10 4SD

May 6–8 BOWNESS-ON-WINDERMERE
**Conference on Computer Simulation** (United Kingdom Simulation Council)
Dr. J. L. Hay, UKSC Conference Secretary, Department of Electrical Engineering, University of Salford, Salford M5 4WT

May 13–16 LONDON
**24th International London Electronic Components Show**
Industrial and Trade Fairs Limited, Commonwealth House, New Oxford Street, London WC1A 1PB

May 20–22 MONTREUX
**International Symposium and Exhibition on Electromagnetic Compatibility**
Prof. Dr. W. Gerber, Box 97, 1820 Montreux, Switzerland

May 22–June 5 MOSCOW
**Communications Systems and Equipment Exhibition SVJAZ-75** (USSR Chamber of Commerce and Industry, 1-a Sokolnichesky Val, Moscow 107732)
British Exhibitors' Joint Venture: BOTB, 1 Victoria Street, London SW1, and EEA, 8 Leicester Street, London WC2

May 23–29 MONTREUX
**9th International Television Symposium**
TVSymposium 1975, Viktoriastrasse 21, CH-3000 Berne 33

* May 26–28 NUREMBERG
**Conference on Technical Reliability** (VDE/NTG)
VDE-Sekretariat, D-6000, Frankfurt/Main 70, Stresemannallee 21.

May 26–30 PARIS
**International Conference on Electronic Instrumentation and Measurements** (FNIE, SEE, UATI)
FNIE, 16 Rue de Presles, 75740 Paris, Cedex 15.

May 27–31 ROTTERDAM
**1st International Communication Exhibition and Congress**
Europort Exhibitions Ltd., 6–7 New Bridge Street, London, EC4V 6AQ; or Europort Tentoonstellinger BV, Waalhaven Z.Z.44, Rotterdam, Netherlands

June 3–5 PARIS
**International Electrical Contracting Conference**
Mr. J. Roper, Electrical Contractors' Association, 55 Catherine Place, London SW1E 6ET

● June 3–6 LONDON *October 1974, p. 572*
**Antennas for Aircraft and Spacecraft** (IEE, IERE, IEEE, IMA, RAeS)
Conference Department, IEE, Savoy Place, London WC2R 0BL

June 11–13 PISA, ITALY
**APL 75—International Congress on Development, Implementation and Application of APL** (National Research Council of Italy, BCS, etc.)
Mr. S. Trumpy, CNUCE, Via S. Maria 36, 56100 Pisa, Italy

June 17–20 MANCHESTER
**Electrical Engineering Exhibition 1975**
Magnum Exhibitions, 157 Station Road East, Oxted, Surrey

June 18–20 PARIS
**International Conference on Fault Tolerant Computing** (IEEE Computer Society, FNIE, SEE and others)
FNIE, 16 Rue de Presles, 75740 Paris, Cedex 15.

June 23–27 LONDON
**4th International Technology Conference and Exhibition – Film 75**
Mr. W. Pay, British Kinematograph. Sound and Television Society, 110 Victoria House, Vernon Place, London WC1B 4DJ

June 30–July 5 TOKYO
**11th International Symposium on Space Technology and Science**
Mr. Shigebumi Saito, Institute of Industrial Science, University of Tokyo, 22–1 Roppongi 7 chome, Minato-ku, Tokyo 106, Japan.

July 1–3 HATFIELD
**International Symposium on the Principles and Applications of Walsh and Other Nonsinusoidal Functions** (Hatfield Polytechnic, IEE, IEEE)
Mr. P. D. Lines, Department of Electrical Engineering, Hatfield Polytechnic, P.O. Box 109, Hatfield, Herts.

● July 21–25 CAMBRIDGE *March 1974, p. 177*
**Conference on Dielectric Materials, Measurements and Applications** (IEE, IERE, IEEE, IoP)
Conference Department, IEE, Savoy Place, London WC2R 0BL

July 29–August EDINBURGH
**International Conference on Physics Education** (IUPAP, UNESCO)
Department of Physics, Mayfield Road, Edinburgh EH9 3JL

August 17–22 EDINBURGH *March 1974, p. 177*
**5th International Conference on Recent Advances in Bio-Medical Engineering** (BES)
Mr. K. Copeland, Biophysics Department, University College London, Gower Street, London WC1E 6BT

August 25–29 SYDNEY, N.S.W.
**International Electronics Convention '75**
The Institution of Radio and Electronics Engineers, Australia, 157 Gloucester Street, Sydney, N.S.W. 2000

September 8–13 CRACOW, POLAND
**4th International Conference of Women Engineers and Scientists—New Techniques in the Service of Mankind**
Mrs. Isabel Hardwich, International Correspondent Women's Engineering Society, 75 Irlam Road, Urmston, Manchester M31 3JU

● September 9–11 LOUGHBOROUGH
**Conference on Hybrid Microelectronics** (IERE, IEE, IoP, ISHM, IEEE)
IERE, 8–9 Bedford Square, London WC1B 3RG

September 9–11 NOORDWIJKERHOUT, THE NETHERLANDS
**International Conference on Physical Aspects of Noise in Solid State Devices**
Dr. G. M. Kleinpenning, Department of Electrical Engineering, University of Technology, P.O. Box 513, Eindhoven, The Netherlands

September 9–12 CARDIFF
**12th Annual Conference on Non-Destructive Testing**
The Non-Destructive Testing Society of Great Britain, Maitland House, Warrior Square, Southend-on-Sea, Essex SS1 2JY

September 9–13 BASLE, SWITZERLAND
**Exhibition of Industrial Electronics and Electrical Engineering**
Schweizer Mustermesse Basel, 4021 Basel, Switzerland

● September 16–19 LONDON
**Conference on Optical Fibre Communications** (IEE, IERE)
Conference Department, IEE, Savoy Place, London WC2R 0BL

September 16–19 SAN FRANCISCO
**IEEE Wescon—Western Electronics Convention and Exhibition**
IEEE Intercon, 3600 Wilshire Boulevard, Los Angeles, Calif. 90010

September 22–26 LONDON
**International Engineering Conference—150th Anniversary of Passenger Railways** (ICE, IMechE, IEE, IRSE)
Secretary, Railway Division, Institution of Mechanical Engineers, 1 Birdcage Walk, London SW1H 9JJ

● September 23–25 BANGOR *August 1974, p. 449*
**Conference on Instrumentation in Oceanography**
IERE, 8–9 Bedford Square, London WC1B 3RG

* September 24–October 2 AMSTERDAM
**HET Instrument 1975**
Het Instrument, P.O.B. 152, Soest, Netherlands

September 29–October 1 TORONTO
**International Electrical, Electronics Conference and Exposition**
IEEE Canadian Region Office, 7061 Yonge Street, Willowdale, Ontario.

October 2–8 GENEVA
**2nd World Telecommunication Exhibition, Telecom 75**
Secretariat-general TELECOM 75, 18, Quai de l'Ecole-de-Medicine, 1211 Geneve 4, Switzerland

* October 6–10 GOTHENBURG
**4th International Trade Fair for the Electrical Engineering Industry —ELFACK**
Joint Venture BEAMA/BOTB: W. Pickett, BEAMA, 8 Leicester Street, London WC2H 7BN

October 10–16 COPENHAGEN
**Elektronik 75**
Press Dept., Bella Centret, 64 Hvidkildevej, DK–2400 Copenhagen NV Denmark

* October 14–16 BRUSSELS
**Second International Symposium on CAMAC in Computer Applications** (ESONE Committee)
Dr. H. Meyer, c/o Commission of the European Communities C.R.C.-CBNM, Steenweg naar Retie, B-2440 Geel, Belgium

November 3–7 PARIS
**International Conference on Biomedical Transducers**
FNIE, 16 Rue de Presles, 75740 Paris, Cedex 15

● November 4–7 LONDON
**Conference on Piezoelectric and Pyroelectric Materials and Applications** (IEE, IERE, IoP, IAE, IEEE)
Conference Department, IEE, Savoy Place, London WC2R 0BL

* November 10–14 MANCHESTER
**Automated Production Exhibition**
Exhibitions for Industry Ltd., 157 Station Rd. East, Oxted RH8 0QF, Surrey

* November 18–20 TEDDINGTON, MIDDLESEX
**Conference on Civil Land Mobile Radio** (IERE, IEEE)
IERE, 8–9 Bedford Square, London WC1 3RG

*● December 1–4 LONDON
**Conference on Signal Filtering**
(IEE, IERE, IoP, IEEE)
Conference Department, IEE, Savoy Place, London WC2R 0BL

December 9–11 LONDON *October 1974, p. 572*
**2nd International Conference on Electrical Safety in Hazardous Environments**
Conference Department, IEE, Savoy Place, London WC2R 0BL

## 1976

● April 6–8 SOUTHAMPTON
**Conference on Applications of Electronics in Medicine** (IERE, IEE, BES)
IERE, 8–9 Bedford Square, London WC1B 3RG

● April 27–30 LONDON
**2nd International Marine Exhibition (IMEX 76) and International Marine Shipping Conference (IMAS 76)**
(British Marine Equipment Council, IMarE)
Brintex Exhibitions Ltd., 178–202 Great Portland Street, London W1N 6NH

April 13–15 LONDON
**The All-Electronics Show**
Evan Steadman, 34–36 High Street, Saffron Walden, Essex CB10 1EP

May 4–8 BIRMINGHAM
**International Instruments, Electronics and Automation Exhibition**
(EEA, BEAMA & Others) Industrial & Trade Fairs, Redcliffe House, Blenheim Court, Solihull, West Midlands B91 2BG

* May 10–14 LONDON *January 1975, p. 88*
**VIIth Congress of the International Measurement Confederation (IMEKO)**
Mr. S. S. Carlisle, Institute of Measurement and Control, 20 Peel Street, London W.8

* June 21–25 CAMBRIDGE
**Conference on On-Line Operation and Optimisation of Transmission and Distribution Systems**
Conference Department, IEE, Savoy Place, London WC2R 0BL

● June 28–July 2 CAMBRIDGE
**Golden Jubilee Convention**
IERE, 8–9 Bedford Square, London WC1B 3RG

* August 29–September 7 BERLIN
**International Radio and Television Exhibition**
AMK Berlin, D1000 Berlin 19, Messedamm 22

* August 30–September 3 EINDHOVEN
**Summer School on Electromagnetics and Antennas**
Ir. E. J. Maanders, Electrical Engineering Department, Eindhoven University of Technology, PO Box 513, Eindhoven, The Netherlands

September 1–3 LONDON
**2nd Conference on Advances in Magnetic Materials and their Applications**
(IEE, IERE, IoP, IEEE)
Conference Department, IEE, Savoy Place, London WC2R 0BL

* September 20–24 LONDON
**International Broadcasting Convention—IBC 76**
(IEE, IERE, EEA, RTS, etc)
IBC, c/o Savoy Place, London WC2R 0BL

* September 2–4 OXFORD *October 1974, p. 572*
**2nd National Quantum Electronics Conference**
(IoP, IERE, IEE, Chemical Society)
Institute of Physics, 47 Belgrave Square, London SW1X 8QX

* November 18–20 LONDON *October 1974, p. 572*
**Conference on Electrical Methods of Machining, Forming and Cutting** (IEE, IMechE, IProdE and others)
Conference Department, IEE, Savoy Place, London WC2R 0BL

# IERE Golden Jubilee Calendar

**1975**
October 23 Institution Banquet in The Guildhall, City of London

**1976**
June 28–July 2 Golden Jubilee Convention at the University of Cambridge

*Further details will be included as they become available.*

# *In Future Issues . . .*

The following papers will be published in forthcoming issues of *The Radio and Electronic Engineer:*

'Evaluation Methods for the Examination of Thick Film Materials'
M. V. Coleman (*Standard Telecommunication Laboratories Limited*)

'Digital Arithmetic Units for a High Data Rate'
P. M. Thompson and A. Bélanger (*University of Ottawa*)

'A Microprocessor-Controlled Interface for Data Transmission'
F. Halsall (*University of Sussex*)

'A Double Phase Sweeping System for Diversity Reception in Mobile Radio'
A. J. Rogers (*Central Electricity Generating Board*)

'Object Identification from Multifrequency Radar Returns'
A. G. Repjar, A. A. Ksienski and L. J. White (*The Ohio State University*)

'A Noise-Protected Digital Heart Ratemeter'
R. J. Twizell (*DSIR, New Zealand*)

'A 150 MHz Transmitter for the Study of Radio Aurora'
C. A. Jenness (*DSIR, New Zealand*)

'A Two-Step Strategy for Character Recognition Using Geometrical Moments'
F. C. Evans and N. D. Tucker (*University of St. Andrews*)

'Diversity Techniques for Mobile Radio Reception'
J. D. Parsons, M. Henze, P. A. Ratliff and M. J. Withers (*University of Birmingham*)

'Dielectric and Conductivity Measurements on Thin Liquid Films of n Heptanol'
J. C. Anderson and R. W. Rennell (*Imperial College of Science and Technology*)

'Series-Parallel Generation of m-sequences'
J. J. O'Reilly (*University of Essex*)

'Linear and Nonlinear Transversal Equalizers for Baseband Channels'
A. P. Clark and U. S. Tint (*University of Technology, Loughborough*)

'The Finite Element Methods for Potential Calculations in a Hall Generator'
G. de Mey (*Ghent State University*)

'A General Study of the Leaky-Feeder Principle'
D. J. R. Martin (*National Coal Board*)

'Electromagnetic Theory of the Leaky Coaxial Cable'
P. Delogne and M. Safak (*Université Catholique de Louvain*)

'Control of Mode Conversions on Bifilar Lines in Tunnels'
L. Deryck (*Université de Liège*)

'Field Leakage and Crosstalk, with Special Reference to Radiating Cables with Perforated Tape Screens'
R. J. Slaughter (*British Insulated Callender's Cables Ltd.*)

'Theory of Transmission of Electromagnetic Waves along Multi-conductor Lines in the Proximity of Walls of Mine Tunnels'
J. R. Wait (*Environmental Research Laboratories, U.S. Department of Commerce*)

'Practical Performances of Radiating Cables'
D. J. Cree and L. J. Giles (*Research and Development Division, British Railways Board*)

'Leaky Coaxial Cables for Communication in High Speed Railway Transportation'
K. Akagawa *et al.* (*Hitachi-Cable Ltd., Japan*)

Reprints of these papers may be ordered from the IERE Publications Department, 9 Bedford Square, London WC1B 3RG, for despatch on publication. Please send remittance with order at the rate of 50p per copy.

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Bungalow 272B, Victoria Road, Lahore.

# International Conference on 'Advances in Automatic Testing Technology'

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**University of Birmingham**

**Tuesday, 15th to Thursday, 17th April 1975**

*The fields to be covered include the following:*

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Further information and registration forms for the Conference will be available in due course from the Conference Department.

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Printed in Great Britain by The Whitefriars Press Limited, London and Tonbridge.